# California's
# Advanced Clean Cars
# Midterm Review

# Appendix C:
## Zero Emission Vehicle and Plug-in Hybrid Electric Vehicle Technology Assessment

January 18, 2017

California Environmental Protection Agency
Air Resources Board

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# I. Introduction and Vehicle Summary

When developing the Advanced Clean Cars (ACC) rulemaking in 2011 for 2018 and subsequent model years, Air Resources Board (ARB or the Board) staff had limited knowledge of how the market would develop. Details of future vehicles including upcoming Ford and BMW products were slim and based mostly from press releases at the time. Since the adoption of the ACC regulations, zero emission vehicle (ZEV, which includes battery electric vehicles, or BEV, and fuel cell electric vehicles, or FCEV) and plug-in hybrid electric vehicle (PHEV) technology has progressed quickly. This has led to introductions (and announcements) of vehicles with longer ranges and more efficient and capable drivetrains far earlier than expected.

The 2010 Joint Agency Draft Technical Assessment Report (2010 TAR) projected ZEV technology and costs, using the Argonne National Labs (ANL) Battery Pack and Costing tool (BaTPaC), and were considered at the time to be aggressive assumptions, even for the 2025 model year.[1] However, indications from other sources and updated work from the 2016 Joint Agency Draft Technical Assessment Report (2016 TAR) [2] shows that those 2010 projections were somewhat conservative. With batteries being a large share of the cost of PHEVs and BEVs, those cost reductions are enabling longer range and more capable versions of those vehicles, earlier than was originally projected. Updated information on FCEV costs was also included in the 2016 TAR; however, FCEVs were not included in the greenhouse gas fleet modeling due to limited sales and higher incremental costs in that timeframe.

Despite impressive cost reductions in batteries, ZEVs and PHEVs are projected to have significant cost premiums relative to future conventional internal combustion engine (ICE) technology. The 2016 TAR projects an incremental cost of $6,500 to $14,200 for PHEV40[3] and BEV200s[4] over an equivalent ICE vehicle in the 2025 model year. While these incremental costs compare similarly to those projected by the 2010 TAR, they represent updated ZEV technology packages. Given market offerings and battery cost reductions, the PHEV20[5] and BEV150[6] packages modeled in the 2010 TAR were updated to PHEV40 and BEV200 packages for the 2016 TAR resulting in an increase in battery content (and associated cost even with the reduced battery prices). For the non-battery components of the PHEV and BEV packages, the costs in the 2016 TAR are largely identical to what was assumed in the 2010 TAR and originally derived from a teardown study of a 2010 Ford Fusion Hybrid conducted by FEV Group (FEV)

[1] EPA 2010. U.S. Environmental Protection Agency, U.S. National Highway Traffic Safety Administration, California Air Resources Board. "Interim Joint Technical Assessment report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025." September 2010. https://www.epa.gov/sites/production/files/2016-10/documents/ldv-ghg-tar.pdf

[2] EPA, 2016. U.S. Environmental Protection Agency, U.S. National Highway Traffic Safety Administration, California Air Resources Board, "Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025," July, 2016. https://www3.epa.gov/otaq/climate/documents/mte/420d16900.pdf

[3] PHEV40 means a 40 mile all electric range (label) PHEV (non-blended)

[4] BEV200 means a 200 mile all electric range (label) BEV

[5] PHEV20 means a 20 mile all electric range (label) PHEV (blended)

[6] BEV150 means a 150 mile all electric range (label) BEV

under contract with the United States Environmental Protection Agency (U.S. EPA). To update these component costs to be reflective of technology improvements since 2010, ARB has a teardown contract currently underway on recently introduced PHEVs and BEVs.

This appendix provides an assessment of the progress of BEV, PHEV, and FCEV technology since the 2012 adoption of the ACC regulations. Section II presents staff's assessment of plug-in electric vehicle (PEV) technologies, which includes BEVs and PHEVs, and components related to these vehicles. Section III includes staff's assessment of FCEV technology.

## *I. A. Past and Current Zero Emission Vehicle Models*

The ZEV market has seen a significant increase in available models since the Nissan Leaf and Chevrolet Volt 2010 market introductions. Currently, the market has increased from one[7] to 25 unique vehicle offerings as of January 2017. Table 1 in Appendix B shows the past and currently available ZEVs and PHEVs.

BEV technology has progressed quickly since the market introduction of the Nissan Leaf in 2010. The Leaf has increased in range by 45% since its first model year. The Tesla Model S has received several increases in range and the addition of a second motor for an all-wheel drive (AWD) version since its market introduction in 2012. The most recent iteration of the Model S is rated at 315 miles of label range[8]. Tesla's Model X came to market at the end of 2015 with AWD, seating for seven passengers, and towing capability. BMW i3 now has an option for a bigger battery pack with even more range. General Motors released its Chevrolet Bolt EV [electric vehicle] on the market at the end of 2016, with 238 miles label range. Several other manufacturers have announced longer range mass market BEVs, with notable examples including the next generation Nissan Leaf, the Tesla Model 3, and a small Ford sport utility vehicle (SUV).

PHEV technology also continues to evolve as manufacturers introduce different architectures and all electric capabilities as they respond to feedback from consumers indicating they want more electric range from the technology.[9] General Motors' second generation Chevrolet Volt was released in late 2015 with 53 miles EPA label all electric range (AER)[10]; an improvement of 15 miles of range over the previous generation. The Volt represents best-in-class technology in terms of range for a PHEV and has been well received by many automotive critics.[11] Vehicle manufacturers have also started to implement PHEV technology on platforms beyond the small and mid-size passenger car segments. Chrysler plans to offer the Pacifica 8-passenger mini-

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[7] One model from a manufacturer subject to the ZEV regulation in 2010

[8] DOE, 2016 U.S. Department of Energy. "Tesla Model S P100D Fuel Economy Online Label" http://www.fueleconomy.gov/feg/Find.do?action=sbs&id=38172

[9] See Appendix B, Section VII for a description of the CVRP Ownership Survey results

[10] EPA label range represents the approximate number of miles that can be travelled in combined city and highway driving, and is based on the UDDS cycle plus several others that represent higher speeds and accelerations as well as colder and hotter weather conditions. To determine PEV range, the vehicle completes a 2-cycle (UDDS) and multiplies the value by 0.7. Values in this document will be EPA label range, unless otherwise noted.

[11] Voelcker, 2016a. J. Voelcker. "Green Car Reports," 16 January 2016. http://www.greencarreports.com/news/1101422_chevrolet-volt-green-car-reports-best-car-to-buy-2016.

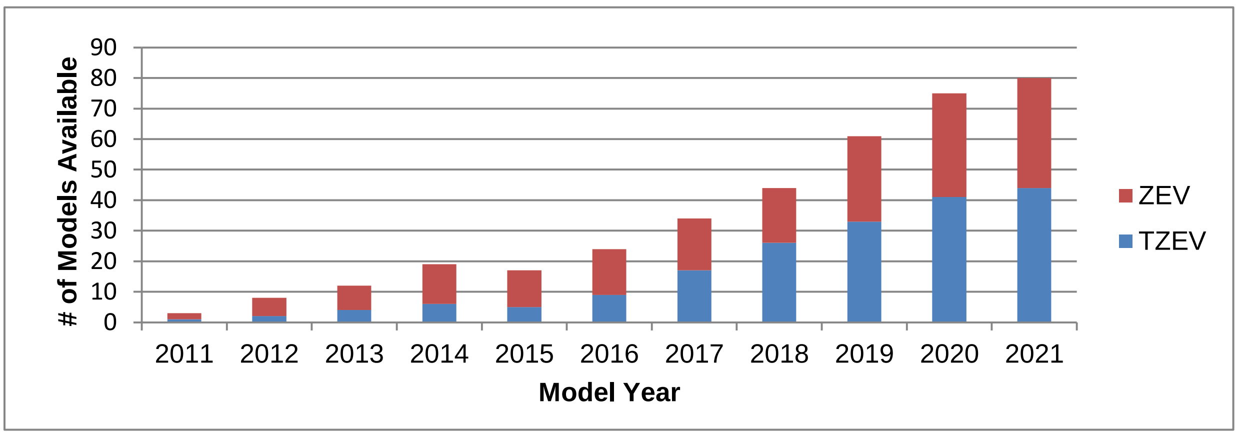
van with a 16kWh battery pack by the end of this year.[12] Volvo currently offers its XC90 7-passenger SUV with an AWD drivetrain and 13 miles label equivalent AER (EAER).[13] Several other manufacturers have also announced plans to offer PHEV options in many of their current and future models.

At the time of the ACC rulemaking in 2012, there were no light-duty mass-produced fuel cell vehicles available on the market. That has changed with introduction of the Hyundai Tucson Fuel Cell in 2015 model year. It was subsequently followed by the releases of the Toyota Mirai and Honda Clarity Fuel Cell.[14] As noted in Appendix D, more than 25 retail hydrogen fueling stations are now open and increases in FCEV deployment are expected over the next several years.

### I.A.1. Future Vehicles

Figure 1 below shows the aggregate number of expected ZEV and PHEV models through the 2021 model year, based on information provided by the manufacturers to ARB as well as public announcements. The figure shows significant growth from 24 vehicle offerings in model year 2016 to approximately 80 vehicle offerings expected by 2021.

**Figure 1 - Aggregate TZEV and ZEV Models by Model Year**




Additional expansion of vehicle model offerings is also expected after 2021, but less certainty is known as manufacturers have not yet solidified plans for those years. However, several manufacturers have announced longer term, broad reaching electrification plans that will affect model years 2022 to 2025, and beyond. Audi, at the 2015 Los Angeles International Auto Show,

[12] FCA, 2016. Fiat Chrysler, "All-new 2017 Chrysler Pacifica Maintains Segment Leadership for FCA US with Upgraded Gas-Powered Model and First Hybrid Minivan," http://media.fcanorthamerica.com/newsrelease.do?id=17218&mid=722. [Accessed 22 August 2016].

[13] DOE, 2016a. U.S. Department of Energy. "Volvo XC90 T8 Fuel Economy Online Label" http://www.fueleconomy.gov/feg/PowerSearch.do?action=noform&path=1&year1=2016&year2=2017&make=Volvo&model=XC90%20AWD%20PHEV&srchtyp=ymm.

[14] Honda, 2016a. American Honda Motor Company, “2017 Honda Clarity Fuel Cell” http://automobiles.honda.com/clarity [Accessed 28 October 2016]

announced that it is committed to achieving 25% of U.S. sales from electric vehicles by 2025.[15] Audi will likely need to develop several more electrified models across its product line to reach such sales goals. In December of 2015, Ford announced that it would be investing $4.5 billion into electrified vehicle solutions.[16] Part of that plan involves adding 13 new electrified vehicle nameplates by 2020, which amounts to more than 40% of the company's global nameplates. Volvo also announced that it has a target to sell one million electrified cars by 2025 which will utilize Volvo's two new modular architectures.[17] While Volvo's specific model plans have not been announced, its 2025 target will likely require many more electrified models than what is available today.

Similar announcements have also come from Daimler, Honda, VW, and the Hyundai Motor Group. In June of 2016, Daimler announced that it would be investing seven billion euros in 'green' technology over the following two years.[18] Daimler subsequently announced the creation of an all new Mercedes-Benz sub-brand "EQ", which will be dedicated to bringing all-electric vehicles to market.[19] Honda's CEO announced in February of 2016 that the company will strive to have two-thirds of the overall sales come from electrified vehicles by 2030.[20] VW announced a new group strategy name "TOGETHER – Strategy 2025" that includes a major electrification initiative with more than 30 new electric vehicles (including Audi) by 2025 and annual sales between two and three million units.[21] The Hyundai Motor Group in April of 2016 announced a new electrification plan that includes 26 new models by 2020. In reference to the announcement, the senior vice president of Hyundai Motor Group's Eco Technology Center said "This is the basement that we will build upon."[22]

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[15] Audi, 2015. Audi of America, "Audi declares at least 25% of U.S. sales will come from electric vehicles by 2025," 18 November 2015. https://www.audiusa.com/newsroom/news/press-releases/2015/11/audi-at-least-25-percent-u-s-sales-to-come-from-electric-2025. [Accessed 8 November 2016]

[16] Ford, 2015. Ford Motor Company, "Ford investing $4.5 billion in electrified vehicle solutions, reimagining how to create future vehicle user experiences," 10 December 2015. https://media.ford.com/content/fordmedia/fna/us/en/news/2015/12/10/ford-investing-4-5-billion-in-electrified-vehicle-solutions.html [ Accessed 8 November 2016]

[17] Volvo, 2016a. Volvo Car Corporation, "Volvo Cars announces new target of 1 million electrified cars sold by 2025," https://www.media.volvocars.com/global/en-gb/media/pressreleases/189874/volvo-cars-announces-new-target-of-1-million-electrified-cars-sold-by-2025. [Accessed 8 November 2016]

[18] Daimler, 2016a. Daimler AG, "Daimler invests massively in green powertrain technologies: All Mercedes-Benz model series will be electrified," 13 June 2016. http://media.daimler.com/marsMediaSite/ko/en/11108480. [Accessed 8 November 2016]

[19] Daimler, 2016b Daimler AG, "Next step in electric offensive: Mercedes-Benz to build first electric car of the new EQ product brand in its Bremen plant," 27 October 2016. http://media.daimler.com/marsMediaSite/ko/en/14353750. [Accessed 8 November 2016]

[20] Honda, 2016b. Honda Motor Co., Ltd. "Summary of Honda CEO Speech on February 24, 2016," 24 February 2016. http://world.honda.com/news/2016/c160224aeng.html

[21] VW, 2016. The Volkswagen Group, "New Group strategy adopted: Volkswagen Group to become a world-leading provider of sustainable mobility," 6 June 2016. http://www.volkswagenag.com/content/vwcorp/info_center/en/news/2016/06/2025.html [ Accessed 8 November 2016]

[22] Greimel, 2016. Hans Greimel, Automotive News, "Hyundai-Kia's grand electrification plan," 4 April 2016. http://www.autonews.com/article/20160404/OEM05/304049949/hyundai-kias-grand-electrification-plan. [Accessed 8 November 2016]

## II. PEV Technology Status and Progress

There have been several advancements in PEV technology that were not originally projected by staff for the 2012 ACC rulemaking (and development of the Federal GHG standards). The 2010 TAR modeled the longest range BEV with up to 150 miles of range (on the EPA fuel economy label) because, at the time, BEVs with 200 miles or more of range were expected to be too expensive relative to a conventional vehicle to be feasible. Additionally, staff assumed in its 2011 ZEV regulation compliance scenario that all BEVs produced in compliance (from 2018 through 2025 model year) would have a 100 mile test cycle range[23] (approximately 70 mile 'label range'), all PHEVs would have 22-40 miles of test cycle range (~14-30 mile label range), and all FCEVs would have at least 350 miles of test cycle range (maxing out the number of credits that could be earned within the program).[24] Since then, multiple manufacturers have announced 200 mile (or more) label range BEVs and multiple PHEVs at various ranges, likely due to decreased batteries costs and increased vehicle efficiency, further discussed in this section.

### *II. A. Industry Targets for PEVs*

The U.S. Department of Energy (U.S. DOE) and U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability (U.S. DRIVE) have both set goals for key PHEV, BEV, and FCEV components which they see as critical milestones to advance the ZEV market.

In order to identify and address some of the challenges faced by the future ZEV market, the U.S. DOE created the Electric Vehicle (EV) Everywhere Grand Challenge, announced by President Obama in 2012. The effort identified several key areas that "can enable the purchase cost combined with the operating cost of an all-electric vehicle with a 280-mile range to be comparable to that of an internal combustion engine vehicle of similar size after five years of ownership".[25] To reach that goal, several targets were established as shown in Table 1.[26]

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[23] Test cycle range means all electric range on the urban dynamometer drive schedule (UDDS).

[24] ARB, 2011a. California Air Resources Board. Initial Statement of Reasons: 2012 Proposed Amendments To The California Zero-Emission Vehicle Program Regulations. December 7, 2011. http://www.arb.ca.gov/regact/2012/zev2012/zevisor.pdf

[25] DOE, 2012a. U.S. Department of Energy, "About EV Everywhere," http://energy.gov/eere/eveverywhere/about-ev-everywhere.

[26] DOE, 2013a. U.S. Department of Energy, "EV Everywhere Grand Challenge Blueprint," U.S. Department of Energy, January 13, 2013. https://energy.gov/eere/vehicles/downloads/ev-everywhere-grand-challenge-blueprint

**Table 1 - U.S. DOE EV Everywhere Grand Challenge 2022 Targets**

| | | Battery | Electric Drive System |
|---|---|---|---|
| | Cost | $125/kWh | $8/kW |
| Energy Density | Volumetric | 400 Wh/L | - |
| | Gravimetric | 250 Wh/kg | - |
| Power Density | Volumetric | - | 4 kW/L |
| | Gravimetric | 2 kW/kg | 1.4 kW/kg |
| | Efficiency | - | 94% |

Recently, the U.S. DOE has begun discussions of draft targets that reach beyond these 2022 targets. While there are minimal details available on the assumptions and methodology of the new targets as they are not yet finalized, U.S. DOE representatives have publicly presented on an aspirational draft target of $80/kWh by approximately 2030 to make BEVs more price competitive with internal combustion engines.[27] Of note, these targets are not projections of battery costs in a specific timeframe but rather cost targets that U.S. DOE has calculated that would need to be achieved for increased price competitiveness of BEVs relative to internal combustion engine vehicles. The agency expects to continue to engage with U.S. DOE as it further updates targets that have helped prioritize and guide innovation in battery and electric drive technology.

U.S. Driving Research and Innovation for Vehicle efficiency and Energy (DRIVE)[28] has also put forth industry targets that align with the EV Everywhere targets. However, these additional targets were established specifically for conventional hybrid electric vehicles (HEV), as ancillary components (interconnects, fuses, etc.) account for a larger percentage of the total system cost, mass, and volume. For BEVs and PHEVs where those ancillary components are a much smaller part of total electrification system, the goals were focused on the components that make up the largest share of the costs. The targets, which were also shown in the 2016 TAR[29] and in Table 2 below, are useful as benchmarks to assess industry's progress on individual components.

[27] Sarkar, 2016. Sarkar, Ruben. U.S. Department of Energy. "The ZEV Imperative: Achieving >80% Decarbonization of Transportation," in FISITA World Automotive Summit, Palo Alto, 2016.
[28] A private/public partnership managed by the U.S. Council for Automotive Research (USCAR) of which the U.S. DOE is a member
[29] EPA 2016.

**Table 2 - U.S. DRIVE 2015 and 2020 Targets for Electrified Components**[30,31]

| | U.S. DRIVE Target (Lab Year) | |
|---|---|---|
| | **2015** | **2020** |
| **Electric Motor** | 1.3 kW/kg | 1.6 kW/kg |
| | $7/kW | $4.7/kW |
| **Power Electronics** | 12 kW/kg | 14.1 kW/kg |
| | $5/kW | $3.30/kW |
| **Motor and Electronics Combined** | 1.2 kW/kg | 1.4 kW/kg |
| | $12/kW | $8/kW |
| **3 kW DC/DC Converter** | 1.0 kW/kg | 1.2 kW/kg |
| | $60/kW | $50/kW |

## *II. B. PEV Technology Trends*

ZEV technology continues to change rapidly as the industry responds to evolving market pressures, consumer demands, and California, U.S., and other global regulatory requirements. Some manufacturers are only now beginning to release first generation ZEV products while others are starting to place their second and third generation vehicles in the market. Those vehicles utilize various technologies that continue to change. This portion of the ZEV technology assessment will focus on batteries, electric motors, on-board chargers (OBC), power electronics, and materials that make advancements in those systems possible. There have also been several broader trends in ZEV technology taking place within the industry: battery packs with increased, energy capacity, vehicle with more electric range, and expanding ZEV technology onto various vehicle segments. All of those things are leading to a wider range of models that offer customers more utility.

### II.B.1. 2016 Technical Assessment Report PEV Findings

The 2016 TAR identified several new trends and reaffirmed several others that were part of the 2012 federal Final Rulemaking (FRM).[32] The first trend noted is that the current BEV market appears to have bifurcated into two segments. The first is a non-luxury segment with prices targeting mass-market segment offerings and an average 85 mile label AER, with significant range increases to beyond 200 miles expected in the next few years. The second is a luxury segment already offering well over a 200 mile label AER. Staff expects both segments to continue to pursue range increases until the manufacturer determines it has found the

[30] The goals were established for the 2015 and 2020 lab years (which are intended to approximate five years before the component would be ready for commercialization and wide-scale mass production).
[31] DRIVE, 2013. U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability. "Electrical and Electronics Technical Team Roadmap," June 2013. https://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap_june2013.pdf
[32] On August 28, 2012, EPA and NHTSA issued a joint Final Rulemaking to extend the National Program of harmonized greenhouse gas and fuel economy standards to model year 2017 through 2025 passenger vehicles.

appropriate combination of range and price that appeals to the largest segment of consumers. Staff expects some manufacturers will likely offer various battery pack sizes on each model, much like Tesla currently does for its Model S and Mitsubishi does for its i-MiEV (in Japan only).

The projection for the amount of range that the furthest BEVs travel on a single charge has changed. The BEV150 category was replaced with BEV200s for the fleet analysis. While PHEV with increased AER were considered to replace PHEV40s (2010 TAR assumption) in the analysis, ultimately, the 2016 TAR analysis modeled PHEV40s due to industry trends and lack of evidence average PHEV range would increase.

There has been an increase in the 20 mile EAER PHEV offerings for the 2015 and 2016 model year in the luxury and performance oriented segments.  Additionally, second generation PHEVs that are now coming to market are offering more AER due in part to customer demands for a more all-electric driving experience.

Electric motor sizing for both BEVs and PHEVs were revised to better reflect what industry is doing. Manufacturers have been able to realize more accelerative performance out of lower power electric motors than what the 2010 TAR modeled. Electric motors were originally assumed to require similar nominal power as an ICE to achieve the same performance. Due to the electric motors ability to make full torque off of idle, the model was revised to use electric motors with lower nominal power ratings and still achieve equivalent vehicle performance.

Reductions in battery costs were realized due to several changes in inputs to the BatPaC model along with other changes to how BEVs and PHEVs were modeled. Version 3.0 of the BatPaC model was released late in 2015 with lowering of raw material input costs, adjustment of cathode technologies, and several other changes. Changes to the vehicle modeling itself included increased state of charge (SOC) windows for BEVs and PHEV40s, increased driveline efficiency, and higher applied aerodynamic drag reductions among other things. Those changes resulted in smaller and lower cost battery packs due to the reduced energy required to achieve the same range, and a lower cost per kilowatt-hour (kWh).

Current and publicly announced near term PEV models span platforms from subcompact cars to large cars, and small sport utility vehicles (SUV) to minivans confirming the technology is available for a large portion of the market segments.  Manufacturers are also using both shared and dedicated platforms for their PEV offerings indicating there is not yet a clearly defined superior approach.  In some cases, use of a global platform allows commonality across models and international markets for increased volumes while in other cases, a dedicated platform allows for a higher level of optimization for the PEV technology.

Even with the advancements, PHEV and BEV models were still not projected to play a significant role in the fleet in the 2016 TAR analysis.  In that analysis, less than 6 percent of the 2025 fleet is expected to be comprised of ZEV or PHEV vehicles and the majority of those vehicles were included in the reference fleet as necessary to meet the ZEV regulation in California (and the Section 177 ZEV states) rather than projected as needed by the U.S. EPA’s OMEGA model to meet the 2018 through 2025 model year greenhouse gas standards.

Other findings noted in the 2016 TAR included acknowledgement that passenger cabin heating and cooling needs as well as battery thermal management systems can have a significant impact on BEV and PHEV energy efficiency and range. Some vehicles, such as the Nissan Leaf, have switched to a heat-pump based heating, ventilation and air conditioning (HVAC) system in place of the more commonplace resistive heating used on PEVs. This method can be more efficient in energy management while satisfying cabin temperature needs. Some manufacturers have also implemented features such as temperature preconditioning of the cabin or battery while the vehicle is still plugged in and more targeted cabin heating systems employing items like heated steering wheels and heated seats to meet driver demands for comfort without expending as much energy to heat the entire cabin.

Direct current fast charging (DCFC) is increasing in availability and popularity, and can support charging at much higher rates than Level 2 (up to 150 kW in some cases, subject to the capability of the vehicle being charged). As range increases for PEVs, DCFC needs are growing fast and may affect usage of Level 2 electric vehicle supply equipment (EVSE); however, there is no universal standard for the DCFC connectors. Those connectors fall into three categories, Society of Automotive Engineers (SAE) International Combo Connector, CHAdeMO and Tesla superchargers[33].

## II.B.2. Battery Pack Energy Capacity Increases

Battery pack capacities have increased in both BEVs and PHEVs, and will likely continue to do so based on manufacturer announcements. Several manufacturers have announced updates of existing BEVs that will include higher energy capacity battery packs. BEV and PHEV battery pack growth by model year is graphically represented in Figure 2 and Figure 3, respectively.

### *II.B.2.i. Examples of Current and Future BEVs with Increased Battery Pack Energy Capacity*

- The 2011 Nissan Leaf was introduced with a 24kWh battery pack. For 2016 model year, Nissan replaced it with a 30kWh battery pack utilizing the same exterior dimensions in some of the trim level variants of the vehicle.[34]
- The Chevrolet Spark EV currently has a battery pack with 19kWh of capacity. The Bolt EV, which is expected to replace the Spark EV, will have 60kWh of energy capacity when it goes on sale at the end of 2016.[35]
- The Tesla Model S battery pack energy capacity options have steadily grown in size since the introduction of the vehicle in 2012. The smaller 60 kWh option grew to 70 kWh in 2015, and then a 75 kWh option was added for 2016. The largest of the initial battery pack offerings (the 85kWh version) also grew to 90kWh in 2015, and a 100kWh version

[33] More information on DCFC and other infrastructure developments can be found in Appendix D.

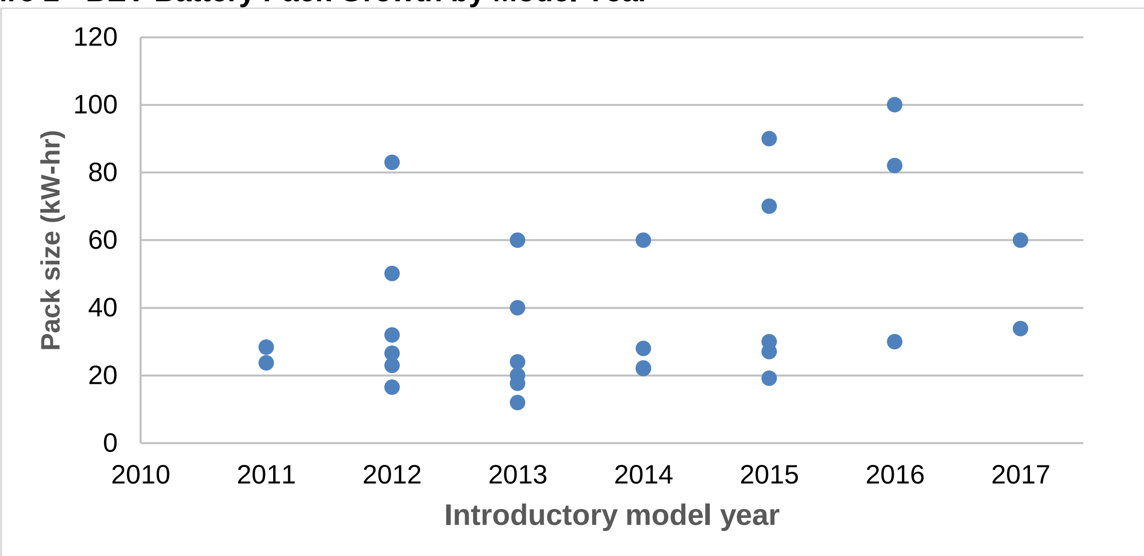
[34] Loveday, 2015. E. Loveday, "Breaking; 30 kwh 2016 Nissan Leaf gets EPA range rating 107 miles," 19 October 2015. http://insideevs.com/breaking-30-kwh-2016-nissan-leaf-gets-epa-range-rating-107-miles/. [Accessed 15 October 2016].

[35] Blanco, 2016. S. Blanco, "Chevy Bolt EV's battery shows big improvements over Spark's," 11 Janaury 2016. http://www.autoblog.com/2016/01/11/chevy-bolt-volt-batteries-similar-different/. [Accessed 15 October 2016].

was announced on August 23, 2016 which customers have already started taking deliveries of[36].

- The 2017 model year BMW i3 will see an increase in its battery pack size from 22 kWh (nominal) to 33 kWh (nominal)[37].
- Ford is expected to update the 2017 model year Focus BEV to be capable of at least a 100 mile label range, an upgrade from the 74 mile label range in the first generation product.[38].
- An executive from the Volkswagen Group stated that its e-Golf will receive a battery pack update from 24.2 kWh to 35.8 kWh for the 2017 model year[39].

**Figure 2 - BEV Battery Pack Growth by Model Year[40]**




### *II.B.2.ii. Examples of Current and Future PHEVs with Increased Battery Pack Energy Capacity*

- Chevrolet increased the size of the battery pack from 16 kWh in its first generation Volt to 18.4 kWh for the second generation of the vehicle. [41]

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[36] Tesla, 2016a. Tesla Motors. "New Tesla Model S Now the Quickest Production Car in the World," 23 August 2016. https://www.tesla.com/blog/new-tesla-model-s-now-quickest-production-car-world. [Accessed 28 August 2016].

[37] BMW, 2016a. BMW Group. "The new 2017 BMW i3 (94 Ah): More range paired to high-level dynamic performance," 2 May 2016. https://www.press.bmwgroup.com/usa/article/detail/T0259560EN_US/the-new-2017-bmw-i3-94-ah-:-more-range-paired-to-high-level-dynamic-performance?language=en_US. [Accessed 28 August 2016].

[38] Voelcker, 2015. J. Voelcker, Green Car Reports. "Updated 2017 Ford Focus Electric: 100-Mile Range, DC Fast Charging,", 10 December 2015. http://www.greencarreports.com/news/1101359_updated-2017-ford-focus-electric-100-mile-range-dc-fast-charging#image=3. [Accessed 29 August 2016].

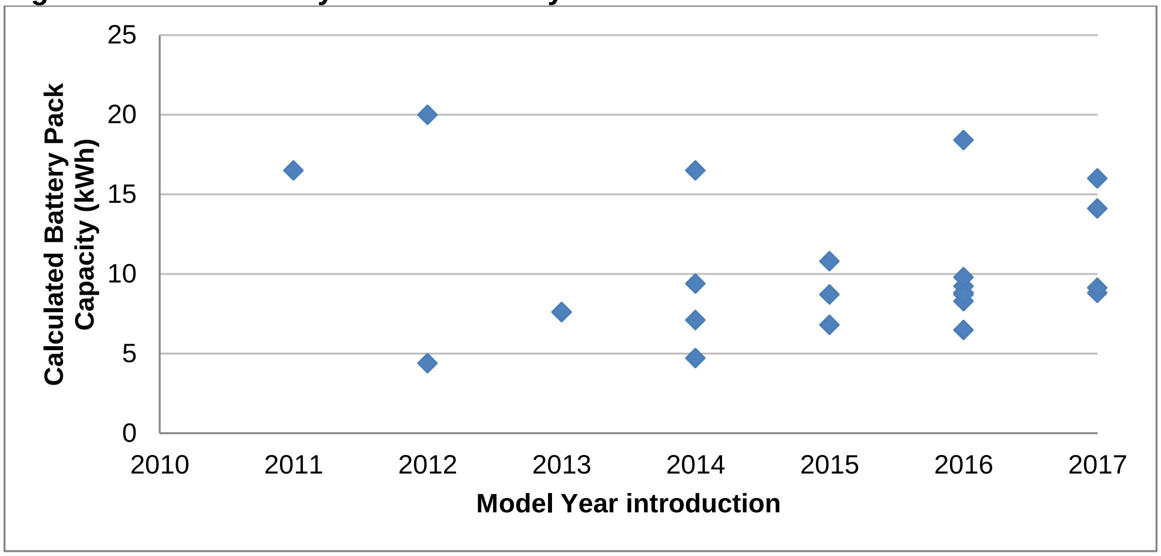
[39] LeSage, 2016. J. LeSage, hybridCARS, "VW Exec Reveals 'Real World' Range of New e-Golf," 23 May 2016. http://www.hybridcars.com/vw-exec-reveals-real-world-range-of-new-e-golf/. [Accessed 29 August 2016].

[40] For vehicles that have been certified by EPA. Incorrect information obtained from http://www.fueleconomy.gov/feg/download.shtml and supplemented by manufacturer

[41] GM, 2016a. General Motors, "Chevrolet Volt - 2016," http://media.chevrolet.com/media/us/en/chevrolet/vehicles/volt/2016.html. [Accessed 15 October 2016].

- The soon to be released Prius Prime has a battery pack with an energy capacity that is twice that of the older 2012 through 2015 model year Prius Plug-In Hybrid; 8.8kWh for the Prime and 4.4kWh for the older Prius Plug-In Hybrid. [42]
- The 2017 model year Porsche Panamera 4 E-Hybrid will have a 14.1kWh battery pack[43] up from 9.4kWh[44] of the previous model year.

**Figure 3 - PHEV Battery Pack Growth by Model Year**




## II.B.3. Vehicle All Electric Range Increases

Vehicle AER has been steadily increasing since the 2012 ACC rulemaking due to the aforementioned battery pack capacity increases, along with efficiency improvements made to drivetrains and associated components. The first generation Chevrolet Volt is one example of range improvements absent a battery change, as its AER increased from 35 miles to 38 miles without any reported change in nominal battery energy capacity. [45] The Nissan Leaf (BEV) was introduced for the 2011 model year with 73 miles label AER, which increased to 75 miles in 2013 model year, and to 84 for 2014 model year with no changes to the battery pack nominal energy capacity. For the 2016 model year, the Leaf with the 30kWh battery pack received another increase to 107 mile label AER.[46] Tesla's Model S has received updates since its introduction for the 2012 model year resulting in increases in range. Other than the increases in

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[42] PluginCars 2016, PluginCars.com "Toyota Prius Plug-In Hybrid (Prime) Review", http://www.plugincars.com/toyota-prius-plugin-hybrid [Accessed 27 October 2016].

[43] Korzeniewski, 2016. Korzeniewski, Jeremy "Porsche Panamera 4 E-Hybrid has 462 hp and 516 lb-ft of torque" 8 September 2015. http://www.autoblog.com/2016/09/08/2018-porsche-panamera-4-e-hybrid/ [Accessed 26 October 2016].

[44] Porsche, 2013. Porsche "New Plug-in Hybrid and Extended Wheelbase Variants Added to Revised Panamera Range" 3 April 2013 http://press.porsche.com/news/release.php?id=776 [Accessed 26 October 2016]

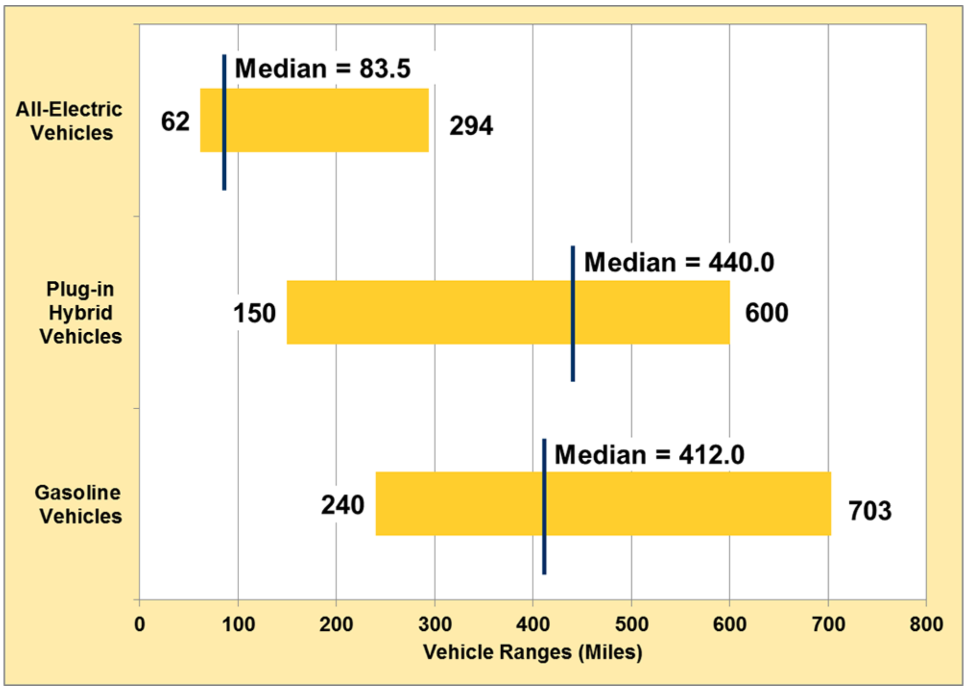
[45] DOE, 2016b. U.S. Department of Energy, "2011 and 2015MY Chevrolet Volts Compared http://www.fueleconomy.gov/feg/Find.do?action=sbs&id=30980&id=35246. [Accessed 29 August 2016].

[46] DOE, 2016c. U.S. Department of Energy, " 2011, 2013, 2014, and 2016MY (30kW-hr battery pack) Nissan Leafs Compared," http://www.fueleconomy.gov/feg/Find.do?action=sbs&id=30979&id=33558&id=34699&id=37067. [Accessed 29 August 2016].

battery pack energy capacity, the Model S has seen range increases resulting from a dual motor AWD drivetrain option amongst other undisclosed efficiency updates. The single motor 90kWh Model S variant was certified by U.S. EPA with 263 miles of range, while the dual motor variant with the same (listed) battery pack capacity was certified at a range of 286 miles; an increase of roughly 8.7%[47].

The U.S. DOE developed a chart, shown in Figure 4 which compares the median range of ZEVs for 2016 model year. Since this figure was released, the maximum range number has changed slightly for the 'All-Electric Vehicles', because Tesla announced its Model S P100D package for 2016 model year that is certified at 315 miles label AER, a significant increase from other Model S vehicle packages.

**Figure 4 - U.S. DOE Chart Comparing PEVs and Conventional Vehicle Ranges for 2016 Model Year[48]**




## II.B.4. Increased Platform and AWD Capability

Industry is also expanding its PEV product offerings into vehicle size, type, and range segments previously unoccupied by any BEV or PHEV. As mentioned previously Volvo introduced its 14 mile EAER XC90 T8 7 passenger AWD PHEV SUV in 2016 model year. Volvo will begin offering that same AWD drivetrain in its S90 large luxury sedan for the 2017 model year with the

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[47] DOE, 2016d. U.S. Department of Energy 2016 “Tesla Model S (90 kW-hr battery pack) and 2016 Tesla Model S AWD - 90D Compared,” http://www.fueleconomy.gov/feg/Find.do?action=sbs&id=37235&id=37240. [Accessed 29 August 2016].

[48] DOE, 2016e. U.S. Department of Energy, "FACT #939: AUGUST 22, 2016 ALL-ELECTRIC VEHICLE RANGES CAN EXCEED THOSE OF SOME GASOLINE VEHICLES," 22 August 2016. http://energy.gov/eere/vehicles/fact-939-august-22-2016-all-electric-vehicle-ranges-can-exceed-those-some-gasoline. [Accessed 7 October 2016].

wagon version, the V90, to follow in late 2017 calendar year.[49,50] Mercedes-Benz introduced the GLE550e 4matic 12 mile label AER PHEV AWD SUV in 2016 model year. BMW brought a PHEV AWD SUV to market for the 2016MY with its X5 xDrive40e, but it is not currently eligible for transitional ZEV (TZEV) credits because the engine is not certified to the required Low Emission Vehicle (LEV) III super-low-emission vehicle (SULEV) 30 emission standard.[51] In January 2017, Chrysler started delivering its 8-passenger Pacifica Hybrid, the first PHEV to be released in the mini-van segment.[52] The Pacifica Hybrid has an EPA certified all-electric label range of 33 miles and qualifies as a TZEV.

Figure 5 shows the number of available and expected ZEV and PHEV (TZEV only) models through 2021. To begin, staff compiled an extensive list of all the currently available models and all of the future models that are expected to be released using publically available news articles. While staff looked at all articles that mentioned the release of potential future vehicles, ultimately this analysis focused on only those vehicles featured in articles that referenced information from an official OEM spokesperson or press release. This analysis was additionally informed in part by confidential meetings with OEMs. In developing this list, staff assumed that each vehicle model would be offered for at least six model years. The figure indicates that the product offerings are expected in broader market segments than currently available and that further increases in range are expected.

Staff was interested in determining model year of the vehicle, likely EPA size classification, and total AER for all future available vehicles. Where this information was not available, an effort was made to compare the vehicle to the current offerings in a manufacturer's lineup or to current best-selling ZEV or PHEV models, typically by using release year referenced to mean model year. In cases where the article projected a release "late" in a calendar year, the next calendar year was chosen as model year. For example, the Chevrolet Bolt EV was released in late calendar year 2016 as a model year 2017 vehicle. Staff utilized the EPA Size Classification[53] for vehicle size as this is information is available as a reference for all current EPA certified vehicles and is a publically available metric. In most cases the stated vehicle range was assumed to be the EPA label range.

[49] Volvo, 2015. Volvo Car Corporation, "Volvo Cars Debuts the S90 Luxury Sedan," 2 December 2015. https://www.media.volvocars.com/us/en-us/media/pressreleases/170061/volvo-cars-debuts-the-s90-luxury-sedan. [Accessed 29 August 2016].

[50] Volvo, 2016b. Volvo Car Corporation, "Volvo Cars reveals stylish and versatile new V90 wagon," 16 February 2016. https://www.media.volvocars.com/us/en-us/media/pressreleases/173662/volvo-cars-reveals-stylish-and-versatile-new-v90-wagon. [Accessed 29 August 2016].

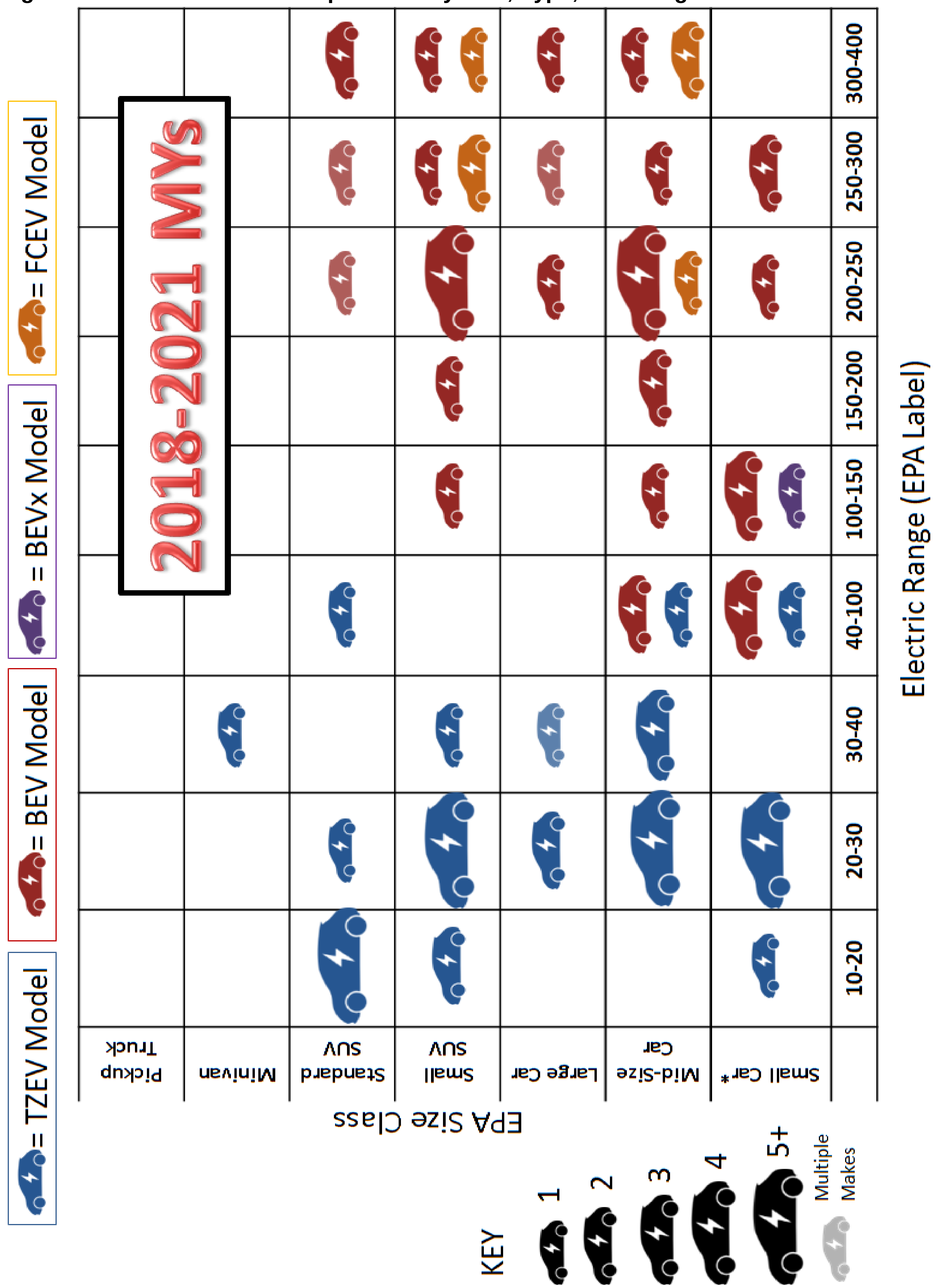
[51] PHEVs are classified in two categories: transitional zero-emission vehicles (TZEV), which must meet super ultra-low-emission vehicle (SULEV) exhaust emission standards, provide an extended warranty on emission control systems, and have zero evaporative emissions in order to qualify for credits under California's ZEV regulation, and non-TZEV PHEVs, which do not qualify to earn credits.

[52] FCA, 2017. Fiat Chrysler. Pacifica Hybrid (Webpage) http://www.chrysler.com/2017/pacifica/hybrid/index.html [Accessed January 13, 2017]

[53] DOE 2016f. U.S. Department of Energy. Fuel Economy Website, Frequently Asked Questions "How are vehicle size classes defined?" https://www.fueleconomy.gov/feg/info.shtml Accessed November 1, 2016

The chart in Figure 5 shows all of the 2018 through 2021 model year vehicles staff expects to be available to consumers based on vehicle technology type (e.g. BEV, BEVx, TZEV, and FCEV), EPA size class, and projected vehicle range. The chart focuses on ZEVs and PHEVs that are TZEV certified and are therefore qualified to be used toward ZEV compliance. The chart is color coordinated based on vehicle technology. In cases where a given model will be available with more than one vehicle range, as is the case with two of the currently available BEV models, a vehicle icon will appear as slightly translucent. The icons are sized relative to the key located on the left side of the chart that indicates the number of models expected in that segment, range, and technology type. In order to reduce the size of the chart, the “Small Car” size classification includes all vehicles that are expected to be classified as a Two-Seater, Minicompact, Subcompact or Compact. Additionally, the Mid-Size Car classification includes several models that are expected to fall within the passenger car segment but publicly available details are insufficient to determine the EPA Size Class.

**Figure 5 - 2018 to 2021MY Unique ZEVs by Size, Type, and Range**




*Small Car combines models designated: Two-Seater, Minicompact, Subcompact, and Compact

## II.B.5. Current State of PEV Specific Technology

Understanding both battery and non-battery technology is critical to understanding the current status of PEVs and where the technology may be headed. Key technologies include battery cells and packs, battery management systems, drive motors, inverters, on-board chargers (OBC), direct current to direct current (DC-DC) converters, PEV specific HVAC components, and high voltage wiring and interconnects. While batteries account for the greatest portion of vehicle cost, non-battery components are essential to the operation of the vehicles.

### *II.B.5.i. PHEV and BEV Cross-Over*

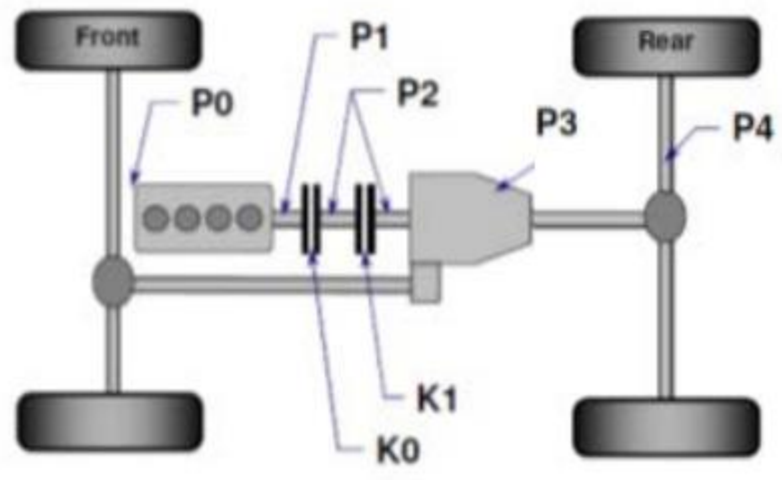
In trying to understand economies of scale and applicability of advancements in individual technologies, it is important to note where PHEVs and BEVs use the same and/or different components. While PHEV and BEV powertrains use similar components, layouts can be quite different. BEV electric machines tend to have a single speed gear reduction gear box centralized between a vehicle's axles. PHEV electric machines usually reside somewhere in the powertrain system, generally with the ICE and its transmission. These basic differences in layout can have an effect on the types and designs of motors, transaxles, battery cells, and power electronics that are used in each technology. Additionally, PHEVs typically have lower power OBC to support lower energy capacity battery packs.

### *II.B.5.ii. Powertrain Layout and Transaxle Configurations*

Many of the differences between BEVs and PHEVs exist in their respective transaxle architecture. All the BEVs on the market use single speed gear reduction transmissions to transmit the electric machine power to the wheels. The designs tend to be relatively simple and compact compared to PHEVs or even more conventional powertrain technologies. BEVs, at the moment, locate the combined electric motor and gearbox at either the front or rear axle. In the case of the dual-motor Tesla Model S, it uses an electric motor and gearbox combination at both the front and rear axles.

PHEVs, in contrast, come in a variety of different formats and configurations. In the case of the systems from Ford, General Motors, Toyota, and Chrysler, they have two electric motors that are packaged in a transaxle assembly designed for a front-wheel drive vehicle (FWD). Other systems being utilized include electric motors located between the engine and transmission (P1 or P2 location in Figure 6), at the axle (P4), or a combination of these locations. A simplified diagram of the typical locations of electric motors in HEVs can be seen in Figure 6.

**Figure 6 - Electric Motor Positions in HEVs**[54]




Shown in Figure 7[55] and Figure 8[56] are the Chevrolet Bolt EV powertrain and the second generation Chevrolet Volt electric powertrain to highlight some of the differences. The Bolt EV, like every currently available BEV, uses an electric motor attached to a single speed gearbox. The Volt, has two electric motors coupled with two planetary gear sets and two clutches in a unit that attaches to the vehicle's ICE. There is additional complexity in the Volt powertrain compared to that of the Bolt EV, both from a mechanical perspective and a controls perspective.

**Figure 8 - Chevrolet Bolt EV Electric Powertrain**

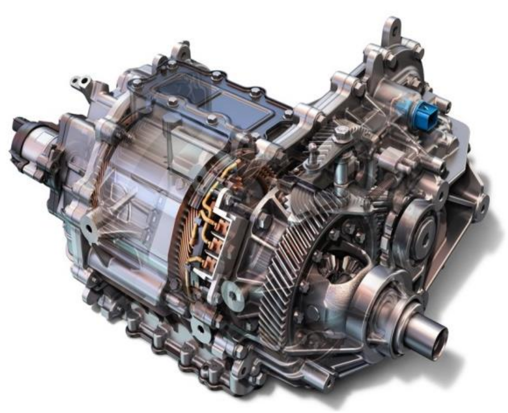


**Figure 7 - Chevrolet Volt (Gen 2) Electric Powertrain**

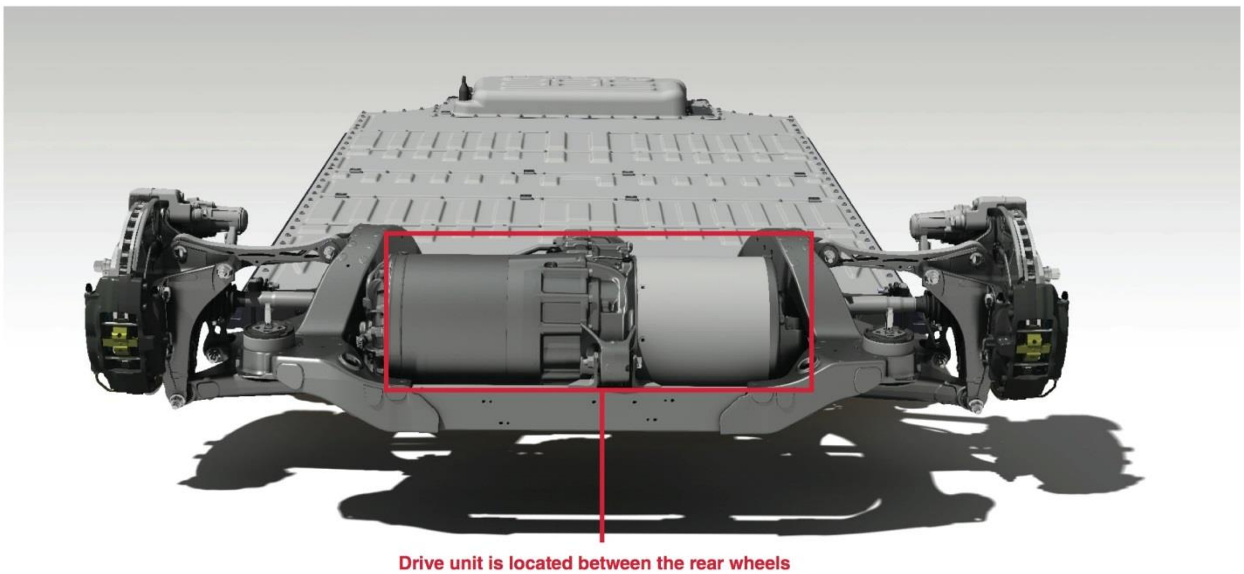
[54] McKay, 2016. P. Brian McKay, "Benefits of a 48V P2 Mild Hybrid," in Advanced Clean Cars Symposium: The Road Ahead, Diamond Bar, 2016. https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/potential_efficiency_and_cost_benefits_of_48v_systems_and_synergistic_technologies.pdf

[55] GM, 2016b. General Motors, Inc. "Drive unit and battery at the heart of the Chevrolet Bolt EV" January 11, 2016. http://media.chevrolet.com/media/us/en/chevrolet/news.detail.html/content/Pages/news/us/en/2016/Jan/naias/chevy/0111-bolt-du.htmlu.html

[56] Nagy, 2014a. Bob Nagy. Kelly Blue Book. "2016 Chevrolet Volt gets new Voltex powertrain" October 29, 2014. http://www.kbb.com/car-news/all-the-latest/2016-chevrolet-volt-gets-new-voltec-powertrain/2000011318/

Two other examples of BEV and PHEV powertrain architecture and layout include the Tesla Model S and Volvo XC90 T8, shown in Figure 9 and Figure 10, respectively. The Tesla Model S rear drive unit includes an electric motor coupled to a single speed gear reduction transaxle packaged with a drive motor inverter assembly. The Volvo XC90 T8 has a FWD 8-speed transmission mated to the gasoline engine and equipped with a crank integrated starter generator (CISG), and an electric rear drive unit in the P4 position that couples a motor, single speed gearbox, and power and control electronics in a single package.

**Figure 9 - Tesla Model S Rear Drive Unit Assembly**[57]




[57] Hutchinson, 2013. L. Hutchinson, "Review: Tesla Motors' all-electric Model S is fast—but is it a good car?," Ars Technica, 27 October 2013. http://arstechnica.com/features/2013/10/review-tesla-model-s/3/. [Accessed 21 October 2016]

**Figure 10 - Volvo XC90 T8 Powertrain Cutaway**[58]

***II.B.5.iii. Electric Machines***

In most cases, both BEVs and PHEVs use permanent magnet electric machines. Induction based electric machines are used in some BEVs, most notably current Tesla models, but rarely in other current installations. The one exception is the upcoming Cadillac CT6 PHEV. It will have one induction electric machine and one permanent magnet machine in its rear-wheel drive (RWD) electric vehicle transmission (EVT).[59]

While most electric machines in BEVs and PHEVs are of the permanent magnet variety, they generally differ in design for many reasons. BEV electric machines are responsible for providing all of the motive power for the vehicle. PHEV systems can be split into two different groups: blended and non-blended. Blended PHEVs do not have an electric drive powertrain that is capable of meeting all of the motive power requirements of the vehicle on electric power only. Non-blended PHEVs, like the Chevrolet Volt, are capable of driving on electric power over the entire range of driving conditions. Non-blended PHEVs require electric machine(s) that are capable of delivering power levels roughly equal to that of the ICE.

With current power densities of electric machines and the size of single gear reduction transaxles, BEV electric machines can be relatively powerful. PHEVs are generally more limited by the space constraints available in a vehicle that also has a gasoline engine and conventional transmission. This leads to differences in sizing and power densities of the motors. Additionally, cooling electric machines in a PHEV when they are packaged in a transaxle that is connected to an ICE can be more complicated due to the heat produced by the ICE.

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[58] Nagy, 2014b. B. Nagy, "2016 Volvo XC90 T8 Twin Engine hybrid shown," Kelley Blue Book, 8 July 2014 http://www.kbb.com/car-news/all-the-latest/2016-volvo-xc90-t8-twin-engine-hybrid-shown/2000010891/. [Accessed 21 October 2016]

[59] Khan, 2016. Khan, A., Grewe, T., Liu, J., Anwar, M. et al., "The GM RWD PHEV Propulsion System for the Cadillac CT6 Luxury Sedan," SAE Technical Paper 2016-01-1159, 2016, doi:10.4271/2016-01-1159.

### *II.B.5.iv. Battery cells*

The battery cells for PHEVs and BEVs also require different things. Due to the power requirements compared to the battery pack size, BEVs require high specific energy from a battery while PHEVs require a balance of energy and power. In almost every case, PHEVs use different battery cells than BEVs. Not only are the physical cell designs and energy capacities different, the variation of lithium-ion chemistry for each vehicle technology is different. Only two manufacturers have used the same battery on their BEV and PHEV: Mitsubishi Outlander PHEV (not available in the U.S.) and i-MiEV, and Honda Accord PHEV and Fit EV. Some OEMs have said they are planning to use the same cell in the future if battery manufacturers are able to meet specific targets; however such solutions appear to be less common as they represent additional compromise on the optimization of the cell to one or both of the applications.

### *II.B.5.v. Battery Packs*

The different energy requirements for BEVs and PHEVs with cost and packaging limitations dictate different battery pack configurations, physical dimensions, and energy contents for the two technologies. There are some common components, like the battery management system, safety disconnects, power wiring, and potentially thermal management systems that could be shared between the two types of vehicles. However, the battery packs between the two vehicle technologies will be different in many ways including the battery cells and the count and configuration of the battery cells due to the electric topology.

### *II.B.5.vi. Inverters*

The power requirements for PHEVs – particularly blended PHEVs - and BEVs will require different drive motor inverters due to the differences in electric power capability of the drivetrains. Designs may be able to be scaled up in power, but the inverters will likely not be the same component.

### *II.B.5.vii. On-Board Chargers*

PHEVs and BEVs have different battery pack energy capacities and very often do not use OBCs with the same power level. Similar to inverters, the device may be able to be scaled up in power, but it will not be the same part. Potentially, smaller OBCs could be operated in parallel to provide more power, as Tesla has done in the past. This could allow an identical lower power level PHEV OBC component to be used in a BEV to provide the power level needed but necessarily results in a less optimized solution.

## II.B.6. Energy Storage Technology- Batteries

Since 2010, manufacturers have coalesced around lithium-ion batteries in virtually every ZEV application with a few notable exceptions. The Toyota Mirai currently uses a nickel metal hydride (NiMH) battery pack very similar to Toyota's Camry Hybrid.[60] However, the fourth generation Prius now offers lithium ion batteries in all but the least expensive trim variant.[61] The

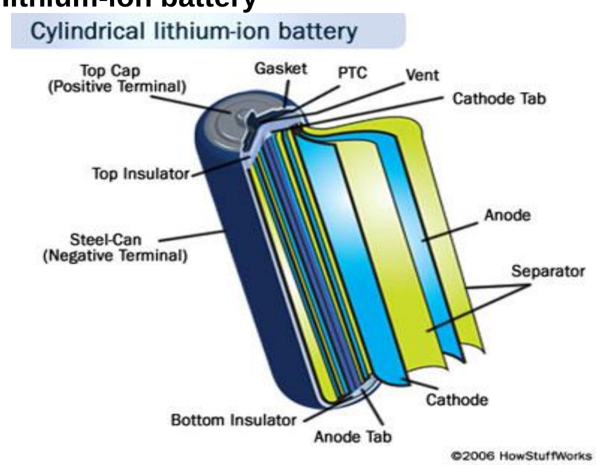
[60] Cunningham, 2014.W. Cunningham, Road Show by CNET. "Toyota Mirai: The 300-mile zero-emission vehicle," 19 November 2014 https://www.cnet.com/roadshow/auto/2016-toyota-mirai/preview/. [Accessed 4 October 2016].
[61] Toyota, 2016a. Toyota Motor Sales, U.S.A, "2017 Prius Features & Specs," http://www.toyota.com/prius/2017/features/mechanical_performance/1224/1223/1228/1227. [Accessed 27 August 2016].

Prius has generally led the way in terms of hybrid technology development of Toyota's hybrid systems. Toyota engineers have more recently indicated that its lithium-ion technology has reached cost equivalency with its NiMH technology, but with more energy density allowing them to pack more energy into a battery pack at a similar cost.[62]

### *II.B.6.i. Lithium-ion Battery Overview*

Lithium-ion batteries are not manufactured in one format. There are currently four different physical battery cell formats that lithium-ion batteries are packaged in; cylindrical, prismatic, pouch, and button formats. For the purposes of this assessment, button cells will not be included, because they are not used in any implementation as an energy storage mechanism for PEV drivetrains. A diagram of a cylindrical cell is shown in Figure 11. Typically, cylindrical cells come in the '18650' format. '18650' cells are an industry adopted cell standard that has the nominal dimensions of 18mm in diameter and 65.0mm in length (for reference, a conventional AA size alkaline battery is typically 14mm in diameter by 50mm in length). Consumer electronics, particularly laptops and battery operated power tools, have made the '18650' battery cell the most widely produced lithium-ion battery format. The demand has driven development, optimization, and volume cost reductions for those cells, which has helped the '18650' cells in Tesla's Model S and Model X vehicles achieve some of the highest energy density and specific energy measurements on the market.

**Figure 11 - Cylindrical lithium-ion battery[63]**



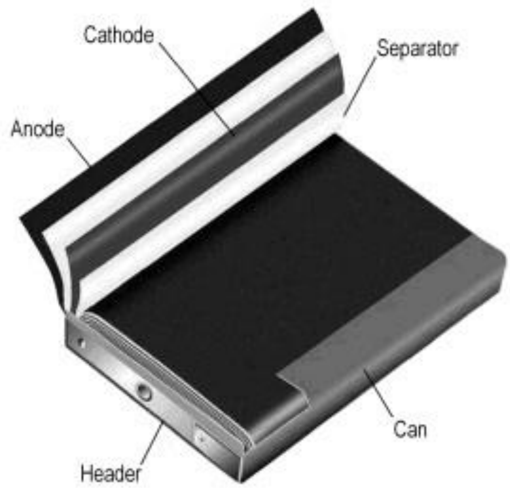

Prismatic battery cells have been designated as such due to their rectangular prismatic shape as see in Figure 12. Prismatic cells have been used in cell phones and some low profile laptops, but also have seen implementations in HEVs, PHEVs, and BEVs. The most notable example is the Toyota Prius, which uses prismatic cells in both NiMH and Lithium-ion variants. Other vehicles that also use prismatic lithium-ion battery cells include the Fiat 500e and the

[62] Tajitsu, 2016, Naomi Tajitsu, Norihiko Shirouzu. Reuters Technology News. "Warming to lithium-ion, Toyota charges up its battery options" 30 October 2016

[63] Brain, 2006. M. Brain, HowStuffWorks.com, "How Lithium-ion Batteries Work," 14 November 2006. http://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery.htm. [Accessed 29 August 2016].

discontinued Honda Fit EV.[64] The prismatic container is designed in such a way that it manages the natural swelling of the components of the cell during charging and discharging. Pressure build-up due to gassing of the components that may occur during cycling of the cell is usually managed through a vent of some kind. While prismatic cells are generally considered to be the safest cell containment design, they give up both specific energy capacity and energy density to cylindrical and pouch cells.

**Figure 12 - Cross Section of a Prismatic Cell**




Pouch cells can be described just like their name indicates. The contents of the cell are sealed within a foil pouch. The pouch is designed to handle the swelling of the components and outgassing, but its external dimensions will change in doing so. This creates additional challenges for packaging considerations when designing battery modules and packs. Nissan Leafs with the 24kWh battery pack use pouch cells packaged as modules that contain four pouch cells. An image of the module is shown in Figure 13. General Motors chose a slightly different design path with its Chevrolet Volt. LG Chem designed and manufactured pouch cells that are more exposed within the pack than the Leaf's enclosed modules. But, that design allows for higher packing density and can better accommodate the liquid cooling design General Motors implemented in the Volt's battery pack. An example of an exposed pouch cell that is used in the Kia Soul EV can be seen in Figure 14

[64]Anderman, 2013. P. Menahem Anderman, "Assessing the Future of Hybrid and Electric Vehicles: The 2014 xEV Industry Insider Report," Advanced Automotive Batteries, 2013.

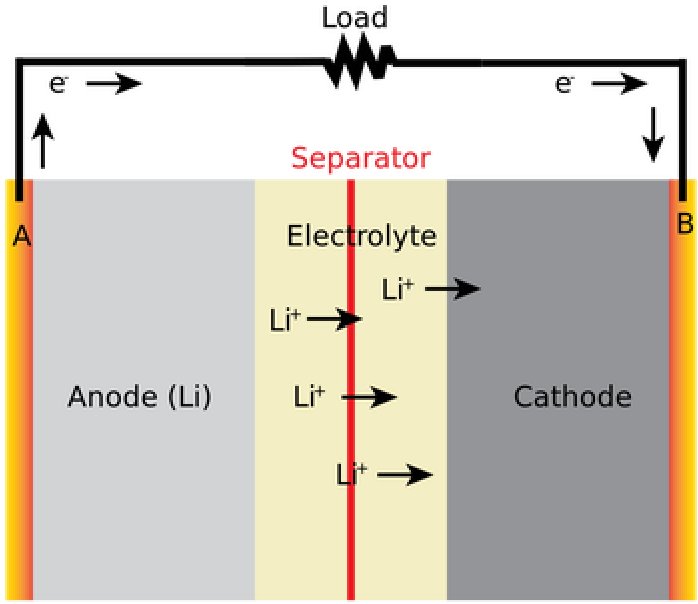
**Figure 13 - AESC Battery Module for Nissan Leaf with 24kWh Battery Pack**[65]

**Figure 14 - SK Innovation Battery Cell Used in Kia Soul EV**[66]


Lithium-ion batteries consist of the following main components: A cathode, an anode, current collectors, a separator, electrolyte, and case of some kind to contain those components. Figure 15 shows how those components comprise a lithium-ion battery cell. It is important to highlight the individual components, because increases in energy or power density often are not from equal improvements in each component. Improvements from technology advancements most often occur within an individual component and result in corresponding changes made to the other components to appropriately handle that change. The equation to determine the theoretical specific energy of a battery can be seen in Equation 1 where $C_A$ is the theoretical capacity of the anode, $C_C$ is the theoretical capacity of the cathode, and $Q_M$ is the specific mass of all the other components. The same equation can be used to calculate energy density if the variables are input in terms of mAh $cm^{-3}$ instead of mAh $g^{-1}$.

[65] AESC, 2016. Automotive Energy Supply Corporation, "Cell, Module, and Pack for Automotive Applications," http://www.eco-aesc-lb.com/en/product/liion_ev/. [Accessed 1 September 2016].
[66] Loveday, 2014. E. Loveday. Inside EVs, "Full Details Released of 2015 Kia Soul EV's "Advanced Battery", 24 February 2014. http://insideevs.com/full-details-released-on-2015-kia-soul-evs-advanced-battery/. [Accessed 1 September 2016].

**Figure 15 - Idealized Lithium Ion Battery**




A/B: Current collectors; negative (A), positive (B)

**Equation 1 - Total Cell Gravimetric Energy Density[67] [1]**

$$\text{Total cell}\,(\text{mAh}\,\text{g}^{-1}) = \frac{1}{(1/C_{\mathrm{A}}) + (1/C_{\mathrm{c}}) + (1/Q_{\mathrm{M}})} = \frac{C_{\mathrm{A}} C_{\mathrm{C}} Q_{\mathrm{M}}}{C_{\mathrm{A}} Q_{\mathrm{M}} + C_{\mathrm{C}} Q_{\mathrm{M}} + C_{\mathrm{A}} C_{\mathrm{C}}}$$

Equation 1 highlights the need for advancements in all three areas in order for energy density and specific energy to increase at a rate similar to increases in both energy capacity metrics of the individual components. If one component sees several large increases and the other two portions do not, those large increases become less and less effective at increasing the total cell energy density or the specific energy of the battery cell.

Lithium ion encompasses several different technologies and variations that use lithium ions as the transport mechanism for electrons. Figure 15 also shows how a lithium-ion battery works. Ions shuttle between the cathode and anode during charging and discharging. Upon discharge, the oxidation of the anode occurs (loss of electrons), and the cathode is reduced (gains electrons). The reverse of those phenomena take place during charging.[68]

[67] Kasavajjula, 2007. U. Kasavajjula, et.al., "Nano- and bulk-silicon-based insertion anodes for lithium-ion secondary cells," Journal of Power Sources, vol. 163, no. 2, pp. 1003-1039, 2007.
[68] Battery, 2016. Battery University, "BU-204: How do Lithium Batteries Work?," Cadex, 3 May 2016. http://batteryuniversity.com/learn/article/lithium_based_batteries. [Accessed 29 August 2016].

### *II.B.6.ii. Current State of Cathodes and Anodes*

Lithium ion battery chemistries with nominal voltages of 3.5V or more are used in the majority of the ZEV products. Cathode variations that are currently being used in the majority of BEV and PHEV applications at those nominal voltages include manganese oxide spinel (LMO), nickel cobalt aluminum (NCA), nickel manganese cobalt (NMC), and NMC-LMO blends. It should be noted that the different cathode chemistries themselves have many variations based on the relative amounts of individual elements within each variations.

Nissan and its battery production company, AESC, chose LMO technology for the battery cells in its Leaf.[69] AESC has made changes to the battery chemistry since the vehicle's introductory 2011 model year, but there have been no reported significant changes in cathode formulation that would change energy density through the 2015 model year. For 2016 model year, Nissan announced a larger, 30kWh battery pack that includes changes to the battery chemistry for increased cell energy density.[70] The Chevrolet Volt in its introductory model year used a LMO dominant/NMC cathode blend.[71] The second generation Volt (2016 model year) kept with a NMC-LMO blend, but had changes made to its cathode formulation, including increased NMC content and a reduction in LMO material.[72]

Industry input to the update of the ANL BatPaC model used in the 2016 TAR has shown that the industry is moving towards higher nickel content NMC for high energy capacity cells.[73] The model was updated to replace the NMC441 cathode option with NMC622 as it is more representative of where the market is going. The 2017 model year Chevrolet Bolt EV will have battery cells that General Motors refers to as 'Nickel-rich' lithium further confirming that manufacturers are moving towards higher nickel content NMC cell.[74] Confidential business information gathered during meetings with OEMs on ZEV technology also confirmed that the cathode material replacement was appropriate for BatPaC, particularly for the near term. Additionally, the model was updated to include a user selectable NMC-LMO blend ratio which better represents the options available to OEMs. Battery cells with varying NMC-LMO blend cathodes are being used in many PHEV and HEV applications in vehicles like the future Chevrolet Volt[75] and Ford Energi products.[76]

[69] AESC, 2016.
[70] GCC, 2015a. Green Car Congress, "New 2016 Nissan LEAF with available 30 kWh pack for 107-mile range," Green Car Congress, 10 September 2015. http://www.greencarcongress.com/2015/09/20150910-leaf.html. [Accessed 17 October 2016]
[71] Brooke, 2014. L. Brooke, SAE International. "GM unveils more efficient 2016 Volt powertrain," 29 October 2014. http://articles.sae.org/13666/. [Accessed 4 October 2016].
[72] GCC, 2014a. Green Car Congress, "First look at all-new Voltec propulsion system for 2G Volt; "the only thing in common is a shipping cap", 29 October 2014. http://www.greencarcongress.com/2014/10/20141029-voltec.html. [Accessed 29 September 2016].
[73] Nuspl, G. et al., "Developing Battery Materials for Next Generation Applications," The Battery Show 2015, Novi MI, 2015.
[74] Liu, 2016. J. Liu, M. Anwar, et. al. *Design of the Chevrolet Bolt EV Propulsion System,* SAE International, 2016.
[75] Howell, 2015. Howell, D., "U.S. DOE Electric Drive Vehicle Battery R&D Impacts, Progress, and Plans," AABC 2015, Detroit MI, June 2015.
[76] Weissler, P., "Electronics diverge in engineering Ford's hybrid C-Max and plug-in Energi," SAE International, January 9, 2013. Retrieved May 5, 2016 from http://articles.sae.org/11705/

For most applications, with the exception of LTO based battery cells that require a specially coated graphite anode, conventional graphite anodes are the industry standard for cost, specific energy, and energy density reasons. However, graphite anodes in most lithium ion battery applications are getting very close to their theoretical energy capacity of 372 mAh/g.[77] Some applications are already reporting values close to 350 mAh/g. Changes in anode chemistry will likely be required to gain any more energy density and specific energy from the anode. One OEM has publically stated that they are already introducing silicon into the anode of their battery cells to improve energy density. Elon Musk, during a conference call, stated "…We're shifting the cell chemistry for the upgraded pack to partially use silicon in the anode. This is just sort of a baby step in the direction of using silicon in the anode. We're still primarily using synthetic graphite, but over time we'll be using increasing amounts of silicon in the anode."[78]

### *II.B.6.iii. Current State of Battery Pack Configurations*

Manufacturers must decide on battery pack topologies, specifically in terms of the number of cells connected in parallel and series. This can be dependent upon a number of factors. Understanding what manufacturers chose to do is critical to knowing what the power demands of the drivetrain will place on individual battery cells, and the voltage range that the battery pack will operate within. Equipment that will operate on the high voltage bus must interface with that voltage, which will have an effect on the cost of that equipment. Increasing the voltage on packs could require voltage isolation specifications of existing equipment to be upgraded to handle the higher voltage. Current standards for CHAdeMO[79] and SAE J1772[80] CCS DCFC equipment limits operating voltages to 500V or less. Any battery pack with an operating voltage higher than that would not be able to use any existing CHAdeMO or SAE CCS fast charging infrastructure without additional equipment on-board the vehicle. To date, many manufacturers have chosen to design battery packs for their PEVs with nominal pack voltages ranging between 300 and 400V.

Battery packs from several of the OEMs are currently configured with 96 cells in series. Known vehicles using that configuration include the Nissan Leaf, Chevrolet Volt and Spark EV, Kia Soul EV, BMW i3, at least one version of the Tesla Model S,[81] and the forthcoming Bolt EV[82] and Chrysler Pacifica Hybrid.[83] The number of parallel strings of cells range from one to five excluding the battery packs from Tesla which use large quantities of '18650' cells in parallel to realize the larger pack capacities. Other PHEVs outside of the Chevrolet Volt and soon to be

[77] Dash, 2016. R. Dash and S. Pannala, "Theoretical Limits of Energy Density in Silicon-Carbon Composite Anode Based Lithium Ion Batteries," Scientific Reports, vol. 6, p. 27449, 2016.

[78] Ruoff, 2015. C. Ruoff, Isentropic Media Charged, "Tesla tweaks its battery chemistry: a closer look at silicon anode development," - 23 September 2015. https://chargedevs.com/features/tesla-tweaks-its-battery-chemistry-a-closer-look-at-silicon-anode-development/. [Accessed 30 September 2016]

[79] IEEE, 2015. IEEE Standards Association. "2030.1.1 – IEEE Standard Technical Specifications of a DC Quick Charger for Use with Electric Vehicles". CHAdeMO.

[80] SAE, 2010. Society of Automotive Engineers International. " J1772 -SAE Electric Vehicle and Plug in hybrid Electric Vehicle Conductive Charge Coupler". January 15, 2010.

[81] INL, 2016. Idaho National Laboratory. "All Powertrain Architecture" https://avt.inl.gov/vehicle-type/all-powertrain-architecture

[82] Liu, 2016.

[83] AABC 2016, Advanced Automotive Battery Conference, Chrysler Pacifica Hybrid Battery Pack Display Information, 15 June 2016

released Chrysler Pacifica Hybrid[84] are using fewer cells in series for their battery packs. The Ford C-Max and Fusion Energi packs both utilize battery packs with 84 cells in series. The Ford Focus Electric and the BMW i3 are both receiving larger battery packs for MY17. The BMW i3 battery pack configuration is receiving new, higher capacity cells, but the configuration of the pack will stay the same.

### *II.B.6.iv. Current State of Battery Pack Thermal Management*

Battery thermal management systems are critical for keeping a battery within its operating temperature range to ensure temperature based battery cell degradation and performance are minimized. The type of system that is used on a vehicle has implications on cost and performance. The efficiency of the system has additional effects on the power required to run such a system, which affects how much additional battery capacity must be allocated just for thermal management. Additionally, thermal management system performance can play a role in how fast a vehicle's battery can be charged, because many lithium-ion chemistries can generate relatively large amounts of heat during high charge load events.

There are two basic types of battery pack thermal management currently in use on vehicles. The first is the passive variety which the Nissan Leaf employs. Nissan chose not to integrate any sort of active thermal management system on the Leaf, and relies on airflow underneath the battery pack, use by the driver, and ambient temperatures to control battery cell temperature.

The second is active systems that can utilize air, liquid, or refrigerant mediums for cooling and heating. Currently available vehicles and the type of battery thermal management each employs are shown in Table 3. Most active air thermal management systems operate in a similar manner; they use a fan to push or pull cabin air through the battery pack. On the other hand, liquid based cooling systems can vary in design. Some systems can function in multiple ways by using different liquid transfer circuits to heat or cool the battery in different ways. Both generations of the Chevrolet Volt use a liquid cooling system that incorporate metal plates between cells which have an ethylene glycol solution that flows through them. The Chrysler Pacifica PHEV that is expected to be released at the end of 2016 uses various devices in the coolant pathway: "To keep the pouch cells at a steady operating temperature, batteries can be heated with glycol/water via a heat exchanger from the engine's cooling system, or a 7-kW heater located in the engine thermal system also can warm the batteries. For cooling, a refrigerant-based a/c chiller system is used. "These heating and cooling techniques mean the battery pack has full-function capability in all climates," said Clark."[85]

[84] Buchholz, 2016a.K. Buchholz, "SAE International," 28 June 2016. http://articles.sae.org/14871/. [Accessed 15 October 2016].
[85] Buchholz, 2016b. K. Buchholz, "2017 Chrysler Pacifica plug-in is industry-first," SAE International, 16 June 2016. [Online]. Available: http://articles.sae.org/14871/. [Accessed 30 September 2016]

**Table 3 - Battery Thermal Management Systems of Available MY16 and Available/Announced MY17 Models**[86,87]

| Manufacturer | Model | Battery Thermal Management Type |
|---|---|---|
| Audi | A3 e-Tron | Liquid |
| BMW | i3 and i3 REX | Refrigerant |
| Cadillac | ELR | Liquid |
| Chevrolet | Volt | Liquid |
| Chevrolet | Spark EV | Liquid |
| Chevrolet | Bolt EV | Liquid |
| Chrysler | Pacifica Hybrid | Liquid |
| Fiat | 500e | Liquid |
| Ford | Focus Electric | Liquid |
| Ford | C-Max and Fusion Energi | Air |
| Hyundai | Sonata Plug-In Hybrid | Air |
| Kia | Soul EV | Air |
| Mercedes-Benz | B-Class Electric Drive | Liquid |
| Mercedes-Benz | S550e | Liquid |
| Mitsubishi | i-Miev | Air |
| Nissan | Leaf | Passive |
| Smart | Fortwo electric drive | Liquid |
| Tesla | Model S and Model X | Liquid |
| Toyota | Prius Prime | Air |
| Volvo | XC90 T8 | Liquid |
| VW | e-Golf | Air |

Table 3 lists the BEV and PHEV (only those that are TZEV certified) models currently on the market, or that will be in the near future, and their respective battery thermal management system type. The majority of models available on the market currently use active liquid type systems. Sustained high temperature is one of the primary drivers of degradation in lithium-ion battery cells, and it seems that many manufacturers are choosing to use liquid thermal management systems to mitigate those effects amongst many other possible reasons.[88]

[86] MB, 2014. Mercedes-Benz. " Mercedes-Benz S550 PLUG-IN Hybrid". September 15, 2014. https://www.mbusa.com/vcm/MB/DigitalAssets/AboutUs/PressReleases/Release_2015_S550_PLUG_IN_HYBRID.pdf

[87] INL, 2016.

[88] Leng, 2015. F. Leng, C. M. Tan and M. Pecht, "Effect of Temperature on the Aging rate of Li Ion Battery Operating above Room Temperature," Scientific Reports, vol. 5, p. 12967, 2015.

## II.B.7. Expected Developments in Energy Storage Technology

Information learned through meetings with OEMs on their upcoming ZEV technology showed that part of the pathway to higher energy density cells will include higher nickel content cells with graphite anodes, and better management of thermal and SOC dependent aging affects. Some OEMs are working with battery manufacturers to implement cells with some silicon added to the graphite anode. There is also potential to begin to see some additional non-conventional lithium-ion based cells in consumer products and PEVs in the near term. OEMs are taking the learnings from the introduction of their first generation battery packs to greatly improve their next generation products.

### *II.B.7.i. Battery Cell Expected Developments*

As was stated previously, the replacement of NMC441 cathodes with NMC622 material in ANL's BatPAC model as used for the 2016 TAR is more aligned with where battery manufacturers are headed. Several OEMs confirmed that the change was appropriate during meetings with ARB, and may be implemented in near term vehicles. In a presentation at the 2016 Advanced Clean Cars Symposium, Sue Babinec, a senior commercialization adviser for the U.S. DOE Advanced Research Projects Agency – Energy (ARPA-E) gave a presentation which displayed the Chinese EV Market Roadmap from Yano Research Institute Ltd. for battery technology. For the year 2020, the roadmap identified NCA and NMC811 cathodes with a composite silicon/graphite anode and a high voltage capable electrolyte (=>4.35V).[89]

Tesla appears to be staying with Panasonic's NCA technology and cylindrical cells. Both Tesla's Chief Technology Officer (CTO) J.B. Straubel and Chief Executive Officer (CEO), Elon Musk have stated that the Gigafactory in Nevada will produce cells in the '2170' format (21mm in diameter and 70.0mm long) for Tesla's upcoming Model 3 BEV.[90] Total Battery Consulting has based its Tesla battery analysis on the larger format and projects a 4.9Ah cell to be used in the Model 3 when it comes to market.[91] This is an increase from the 3.4Ah '18650' format cells that are currently used in the Model S and Model X.

A near term potential improvement in batteries may come via silicon. Pure silicon anodes have tremendous potential in terms of theoretical specific energy. The fully lithiated phase of silicon at room temperature shows a maximum capacity of 3579 mAh/g compared to the 372 mAh/g for graphite. The lithiated silicon undergoes massive volume expansion of up to 280%.[92] Such a volume change would quickly cause mechanical damage to the anode's solid electrolyte interphase (SEI) and to its connection with current collector. Despite the volume expansion

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[89] Babinec, 2016. S. Babinec, "Energy Storage Technology for Transportation," in *Advanced Clean Cars Symposium: The Road Ahead*, Diamond Bar, CA, 2016. https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/advancements_in_liion_technology_andor_manufacturing_sue_babinec.pdf

[90] Farhenbacher, 2016. K. Farhenbacher, "Fortune.com," 27 July 2016. http://fortune.com/2016/07/27/tesla-bigger-battery-gigafactory/. [Accessed 15 October 2016].

[91] Anderman, 2016. Dr. Menahem Anderman, "xEV Expansion, Technology, and Market Outlook" in Advanced Automotive Battery Conference, Detroit, 2016

[92] Lee, 2016. J. K. Lee, et. al. "Rational design of silicon-based composites for high-energy storage devices," Journal of Materials Chemistry A, vol. 4, no. 15, pp. 5366-5384, 7 March 2016.

issue, battery manufacturers are finding ways to integrate silicon into graphite anodes in small but increasing amounts to increase energy density.

As noted earlier, Tesla has reportedly started using battery cells that have some silicon in the anode. During meetings with other manufacturers, some stated that adding silicon to the graphite in the anode provided a pathway to increasing energy density, but it was unclear whether those cells would be in products before 2021.

More energy dense battery cells are also becoming available as a result of many undisclosed changes to cell chemistry and makeup. The 2017 model year BMW i3 and i3 REX are receiving a more energy dense battery pack made possible by new Samsung SDI cells that increased from 60Ah to 94Ah in energy resulting in longer range vehicles for customers. The physical dimensions of the battery remain the same which allows for much simpler implementation of the new battery in the same vehicle design.[93] The second generation Chevrolet Volt is also using higher energy content cells in its battery pack compared to the first generation vehicle. The individual cells grew from 15.5Ah to 26Ah which allowed General Motors to cut down on the total number of cells by one third, and still grow the total battery pack energy capacity from 16.5kWh to 18.4kWh.[94] The additional energy capacity is one the primary reasons the new Volt's AER increase. With no change in the number of cells or electrical topology, the 2016 model year Nissan Leaf pack increase relates directly to the same percentage increase in cell size; a 25% increase in battery cell capacity which translates to an increase from 32.5Ah on the 24kWh pack to more than 40.5Ah in the new 30kWh pack.[95,96] During meetings with OEMs about their forthcoming ZEV technology, some indicated that they would be using increased capacity cells as they became available with their PHEV products.

### *II.B.7.ii. Expected Battery Pack Developments*

OEMs are moving towards higher cell count modules to reduce material usage and improve packing efficiency. The 2016 model year Nissan Leaf's 30kWh battery pack received a few internal design changes, one of which increased the number of cells per module from four to eight.[97] Nissan showed a prototype 60kWh battery pack for the Leaf at the 2015 Tokyo Auto show. The pack was said to have 288 cells with what looked like 16 discrete modules.[98] If the pack is any indication of what a 60kWh Leaf pack may look like then the number of cells per module for the new pack will likely increase beyond the eight per module in the current 30kWh Leaf pack. The higher number of cells in a module can potentially reduce costs and as seen in the Leaf, help to increase the energy density of the battery pack.

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[93] BMW, 2016a.

[94] Conlon, 2015. B. M. Conlon, et. al. "The Next Generation "Voltec" Extended Range EV Propulsion System," Journal of Alternative Powertrains, vol. 4, no. 2, pp. 248-259, 14 04 2015.

[95] AESC, 2013. Automotive Energy Supply Corporation, "Cell, Module, and Pack for EV Appliations," 2013. http://www.eco-aesc-lb.com/en/product/liion_ev/. [Accessed 12 October 2016]

[96] Nissan, 2016. Nissan North America, Inc., "2016 Nissan LEAF Press Kit," 2016. http://nissannews.com/en-US/nissan/usa/presskits/us-2016-nissan-leaf-press-kit. [Accessed 12 October 2016]

[97] Nissan, 2016.

[98] Cole, 2015. J. Cole, Inside EVs, "Nissan IDS Concept: "The Future Nissan LEAF In Drag", 60 kWh NMC Battery Inside," 30 October 2015. http://insideevs.com/nissan-ids-concept-future-nissan-leaf-drag-report/. [Accessed 13 October 2016].

The Chevrolet Bolt EV and Volt are two other examples of the trend to increase the number of cells per module. The Bolt EV has two different module sizes. One with three parallel cells arranged with ten groups in series for a total of 30 cells, and another with three parallel cells with eight groups in series for a total of 24 cells in the module.[99] The first generation Volt had nine modules with either 18 or 36 cells per module. The second generation Volt has fewer modules, but its smallest module size is up to 24 cells, and the larger module down to 32 cells.[100] Chrysler had its Pacific Hybrid battery pack on display at the 2016 Advanced Automotive Battery Conference in Detroit, Mi. The pack looked to have 6 distinct similar modules and claimed to have a configuration of 96 cells in series.

### *II.B.7.ii.1. Higher Voltage Packs*

Porsche displayed its Mission E concept BEV at the International Auto Show in Frankfurt, Germany on September 15th of last year, 2015. The concept was said to have an 800-volt battery system that Porsche claimed "offers multiple advantages: shorter charging times and lower weight, because lighter, smaller gauge copper cables are sufficient for energy transport."[101] The Mission E was then greenlighted for production by the end of the decade on December of 2015 with Porsche specifically calling out the 800-Volt energy storage system again on the vehicle. At the 2016 Advanced Automotive Battery Conference (AABC), Porsche development engineer, Dr. Christian Jung, gave a presentation entitled "The Future of EVs and Fast Charging at 800V". The presentation showed that Porsche is moving along with developing the 800-Volt hardware – most of which Porsche stated was already capable of the higher voltage - to support a battery pack that operates around that voltage. Their 800-Volt pack was stated to have lost 40kg of mass from a 400-Volt version due to reductions in copper and cabling. The presentation also made the case that higher voltage technology is the enabling piece for DCFC at rates over 200kW. The production version of the Porsche Mission E may be the introduction of a technology that will allow for DCFC up to 350kW and the faster battery charge times that come with it.

### *II.B.7.ii.2. Battery Pack Thermal Management*

OEMs are also redesigning battery thermal management systems and cell packaging. Rather than use the slim liquid cooling plates that sit between cells, the new Bolt EV battery pack uses what General Motors calls 'Conductive Solid Fins'. The conductive fins are connected to a liquid thermal management system where the heating, cooling, and pumping mechanisms reside outside of the battery pack. While the conductive fins may be slightly less effective at removing or adding heat to the individual cells, the design takes advantage of the greater thermal capacitance of the Chevy Bolt EV's entire battery pack compared to that from the Chevy Spark

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[99] Smith, 2016. G. Smith, "Battery System for the Chevy Bolt," in Advanced Automotive Battery Conference, Detroit, 2016

[100] GM, 2016c. General Motors, "2016 Chevrolet Volt Battery System," https://media.gm.com/content/dam/Media/microsites/product/Volt_2016/doc/VOLT_BATTERY.pdf. [Accessed 13 October 2016].

[101] Porsche, 2015. Porsche AG, "World premiere for Porsche Mission E," Porsche AG, 14 September 2015. [Online]. Available: https://newsroom.porsche.com/en/products/iaa-2015-porsche-mission-e-mobility-all-electrically-concept-car-11391.html. [Accessed 12 October 2016].

EV. The Chevy Bolt EV's battery pack thermal management methodology allows the entire battery pack to be simpler and easier to assemble than it would have been otherwise.[102,103]

Another example of modifications to thermal management systems comes from Tesla which further indicates an area that other OEMs may be concentrating on for ZEV and PHEV models in the near term. On August 23, 2016, Tesla announced the introduction of the P100D version of its Model S. The new battery pack has been stated to have redesigned cell modules to increase the packing density which includes changes to the thermal management system. The previous highest energy pack from Tesla was its 90kWh version. Elon Musk, in reference to the design changes that enabled the increase in total pack energy stated "The cell is the same, but the module and pack architecture is changed significantly in order to achieve adequate cooling of the cells in a more energy dense pack and to make sure we don't have cell to cell combustion propagation."[104] Those improvements in thermal management can help batteries to last longer, work more consistently and efficiently, and improve vehicle safety. As a result of the cell and pack level technological developments, manufacturers are increasing the density of their battery packs on both a volume and mass basis.

The second generation Chevrolet Volt battery increased its volumetric energy density from 118Wh/l to 119Wh/l and its mass based energy density from 87Wh/kg to 101Wh/kg.[105] The Chevrolet Bolt EV also realized large improvements over the Spark EV. The Bolt EV's battery pack has a volumetric energy density of 210 Wh/L versus 137Wh/L for the Spark EV, and mass based energy density of 138Wh/kg versus 88Wh/kg for the Spark EV.[106,107,108] The Chrysler Pacifica Hybrid pack shown at AABC 2016 was stated to have a volumetric energy density of 113Wh/L and 100Wh/kg which is roughly the same as the second generation Volt pack. These recent developments coupled with the other aforementioned advancements in this section likely indicate the direction and scale of improvements that other OEMs will take with their future near-term products.

### II.B.8. Potential Long-Term Developments in Energy Storage Technology

Battery technology developments over the longer term are much less certain. There is an enormous amount of ongoing research to develop a better battery. While there are lots of promising advancements happening in research labs around the world every day, there is unlikely to be a 'silver bullet' that will suddenly meet the U.S. DOE EV Everywhere goals for

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[102] Guerin, 2016. J. Guerin, "Battery System Design Considerations Between the Chevrolet Spark EV and the Bolt EV," in *Advanced Automotive Battery Conference*, Detroit, 2016.
[103] Smith, 2016.
[104]Voelcker, 2016b. J. Voelcker, Green Car Reports, "Why new Tesla 100D battery may be crucial for the Tesla Model 3," 12 September 2016. http://www.greencarreports.com/news/1105926_why-new-tesla-100d-battery-may-be-crucial-for-the-tesla-model-3. [Accessed 11 October 2016].
[105] GM, 2016c
[106] Liu, 2016.
[107] GM, 2015. General Motors, Inc. "2016 Chevrolet Volt wins second Green Car of the Year award" November 2015. http://media.chevrolet.com/media/us/en/chevrolet/bcportal.html/currentVideoId/4622082940001/currentChannelId/Most%20Recent.gsaOff.html
[108] GM, 2016d. Chevrolet, "Chevrolet Product Information: 2016 CHEVROLET SPARK EV," 2016. http://media.chevrolet.com/content/media/us/en/chevrolet/vehicles/spark-ev/2016/_jcr_content/iconrow/textfile/file.res/16-PG-Chevrolet-Spark-EV.pdf. [Accessed 13 October 2016]

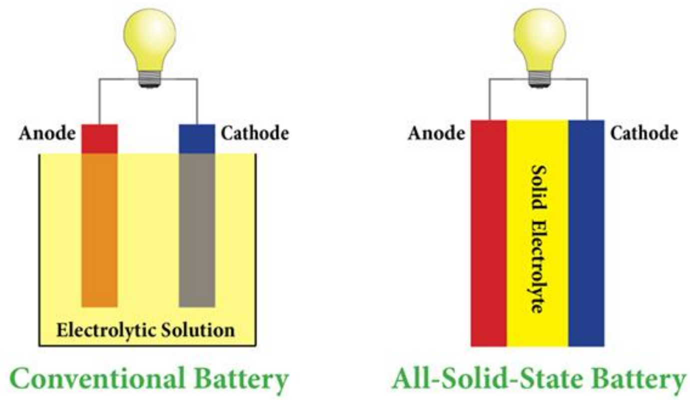
energy storage technology. Several OEMs indicated to staff that the pathway towards a better battery will include nickel-rich NMC cathodes (like NMC622 or NMC811) coupled with graphite anodes that contain increasing amounts of silicon. That pathway will likely be combined with improvements in other internal cell components like binders and electrolyte formulations to enable higher energy and power densities.

The U.S. DOE Vehicle Technology Office (DOE VTO) Advanced Battery Research and Demonstration Program is focusing funding for the 2016-2020 time period on silicon anode technology with high-voltage cathodes to achieve those 2022 DOE goals. The DOE believes that there is a clear pathway towards meeting the 2022 goals which includes higher voltages cathodes, intermetallic anodes, and expanded work on lower cost materials, electrode, and cell manufacturing. For beyond 2022, the DOE VTO will continue to focus on Li-metal and solid state battery research.[109] A few other potential longer term technologies include lithium sulfur (Li-S) based chemistries, lithium-air ($LiO_2$), redox flow, and multivalent intercalation chemistries.

Solid state batteries, which are generally lithium-ion based, replace the electrolyte and separator in a battery cell with a solid material. That material is usually a type of polymer or ceramic. Solid state cells potentially can work with a variety of different anodes and cathodes and have several potential technical advantages. An example of an idealized conventional battery and all-solid state battery can be seen in Figure 16. Current lithium-ion battery cells use electrolytes that are flammable under extreme conditions. By replacing that electrolyte with a solid material that is not flammable, the cell can then withstand extreme abuse. Seeo, a battery startup that was purchased by Robert Bosch General MotorsbH (Bosch) in August of 2015 displayed some of the abuse testing on their solid state Li-metal - LFP cells at the 2016 Advanced Automotive Battery Conference (AABC) in Detroit, Michigan. The cells exhibited no smoke or flames under crush, penetration, short circuit, thermal shock, over-discharge, or overcharge testing. The cells also showed thermal stability up to 180 degrees Celsius.[110]

[109]Howell, 2016. D. Howell, B. Cunningham, T. Duong and P. Faguy, "Overview of the DOE VTO Advanced Battery R&D Program," in U.S. DOE Annual Merit Review, Washington D.C., 2016
[110] Gross, 2016. D. J. Gross and D. H. Eitouni, "Drivers and Technologies for Li-Metal Solid-State Batteries," in *Advanced Automotive Battery Conference*, Detroit, 2016

**Figure 16 - Comparison of Idealized Conventional Battery to Idealized Solid State Battery**[111]




Another potential advantage of a solid state design is the possibility for bi-polar stacking. Instead of having separate, discrete cells that must be connected in series via bus bars, the cells themselves are layered on top of each other with the cathode of one cell set atop the anode of another cell. Bipolar designs have the potential to minimize IR losses between adjacent cells in a bipolar cell stack. There is a large amount of potential to minimize packaging materials and total volume with a bipolar solid state cell stack. And, with the potential high levels of safety inherent to the solid state cells, they could be packaged in crush zones on a vehicle. The packaging opportunities could give manufacturers more flexibility with vehicle designs to increase passenger and cargo utility.

Solid state technologies are not without significant barriers. One of those includes the much greater resistance to ion mobility of the solid state electrolyte. As a result, current solid state cells exhibit very low specific power and power density relative to conventional lithium-ion batteries. Often times, a solid-state battery requires a higher operating temperature to be able to charge or discharge at any reasonable rate, which makes it impractical for electrified vehicle applications where a battery heater would have to run constantly.

Several companies are currently developing solid state battery cell technology targeting commercialization as soon as possible. Some of those companies have been purchased by larger corporations. Sakti3, a startup spun out of the University of Michigan was acquired by Dyson in October of 2015 for $90 million.[112] As was mentioned earlier, Seeo was purchased by Bosch last year. There are many other companies working on solid state technology, some of which include Solid Power, 24-M, Ilika, PolyPlus, and Toyota.

At the 2016 AABC, Dr. Juergen Gross of Robert Bosch General MotorsbH (Bosch) gave a presentation entitled “Drivers and Technologies for Li-Metal Solid-State Batteries.” The presentation, in part, covered Seeo’s battery technology that Bosch now owns. Cycle life testing

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[111]Morris, 2016. C. Morris, "Researchers use superionic conductors as electrolytes for solid-state batteries," Charged Electric Vehicles Magazine, 2016

[112] Sawers, 2015. P. Sawers, "Dyson acquires Sakti3 for $90M to help commercialize ‘breakthrough’ solid-state battery tech," Venture Beat, 19 October 2015. http://venturebeat.com/2015/10/19/dyson-acquires-sakti3-for-90m-to-help-commercialize-breakthrough-solid-state-battery-tech/. [Accessed 18 October 2016]

of the Li metal – LFP cells showed impressive results. However, no details were given on the specific energy and power, or the energy and power densities. But, according to the presentation, Bosch believes that they will have a solid state cell ready for series production after 2020 to meet the needs of the market.[113]

Yuki Kato of Toyota Motor Europe NV/SA also presented at the 2016 AABC on Toyota's development of its solid state technology. Yuki Kato and other team members recently published their work in Nature Energy entitled "High-power all-solid-state batteries using sulfide superionic conductors".[114] The test cell displayed very little internal resistance, especially at 100 °C, and the ability to operate at extremely high current densities. The paper claims stable cycling of the cell at up to 18C. In the presentation given at the AABC, charts dispalyed discharge curves with current densities well beyond that. Toyota appears to have made major headway towards surpassing one of the major barriers for solid-state batteries.

24M has designed what the company calls a semi-solid lithium-ion battery. The company set out to simplify the internal structure of a lithium-ion battery to make is faster and cheaper to produce. The semisolid electrodes require no drying and the company claims it takes one-fifth of the time for conventional lithium-ion to go from components to cell. 24M's technology has the potential to significantly reduce the cost of producing battery cells.

As part of ARPA-E's BEEST program, 24M received funding to develop their technology. ARPA-E's Project Impact Sheet identified the cell as having two thick (450µm) electrodes; the anode is graphite and the cathode is LFP. The project, which lasted from September 2010 to February 2014, concluded "with the successful delivery of a 17Wh cell that... cycled at a high efficiency (more than 85% roundtrip), and showed reasonable cycle life (more than 1000 cycles) with limited capacity loss. 24M has designed the cell to operate at a continuous charge/discharge rate of C/4, and have also shown good performance in grid duty cycles with sustained power pulses of up to 2C."[115] 24M was awarded another round of funding by the U.S. DOE in October 2014 to further develop its manufacturing processes. The project concluded with 24M delivering cells on a process that operated with a 96% yield beating its target of 85%.

24M entered into a MoU with NEC Energy Solutions, Inc. (NEC ES) in October of 2015 to supply the semisolid lithium-ion cells for the NEC ES integrated storage systems. In October of this year, 2016, 24M delivered an initial batch of production-sized cells to NEC ES for testing and validation. If things continue as expected, 24M will begin delivering production cells to NEC ES sometime next year (2017)[116]. 24M has also received more funding to further develop its

[113] Gross, 2016.
[114] Kato, 2016. Y. Kato et. Al. "High-power all-solid-state batteries using sulfide superionic conductors," Nature Energy, vol. 1, pp 16030, 21 March 2016, http://dx.doi.org/10.1038/nenergy.2016.30.
[115] ARPA-E, 2016a. U.S. DOE ARPA-E, "PROJET IMPACT SHEET - ENHANCED BATTERY CELL PERFORMANCE AND AUTOMATED CELL FABRICATION," 14 April 2016. https://arpa-e.energy.gov/sites/default/files/documents/files/18%20%2024M%20-%20BEEST%20External%20-%20Project%20Impact%20Sheet_FINAL.pdf. [Accessed 19 October 2016].
[116] BW, 2016. Business Wire, "24M Delivers Initial Quantity of Production-size Semisolid Lithium-ion Cells to NEC Energy Solutions for Testing and Validation," Business Wire, 12 October 2016. [Online]. Available: http://www.businesswire.com/news/home/20161012005153/en/24M-Delivers-Initial-Quantity-Production-size-Semisolid-Lithium-ion. [Accessed 19 October 2016].

technology. USABC with the U.S. DOE awarded 24M with $7 million over 36 months in June of this year (2016) to demonstrate that its approach to cell design and manufacturing can meet the USABC 2020 battery targets for EV applications.[117]

Lithium metal anodes are another area that has significant potential to improve batteries. Unfortunately, lithium metal anodes like to form dendrites (tree-like structures made of lithium metal in this case) that quickly reduce the battery's ability to store energy. Solid state batteries potentially could help with dendrite formation by mechanically restricting the ability of the dendrite to form. The PolyPlus Battery Company in a partnership with SCHOTT North America was awarded grant funding from ARPA-E to "develop thin electrodes made of lithium foil protected by a flexible Li-ion conductive glass separator sheet... The approach is based on PolyPlus' proprietary Li-metal/glass electrode technology, and takes full advantage of commercially scalable glass sheet manufacturing techniques to produce a highly conductive separator that prevents the formation and propagation of dendrites in a lithium metal battery cell."[118] Finding ways to restrict dendrite growth in lithium metal anodes is one the barriers to viable batteries utilizing the technology.

SolidEnergy Systems Corp. was also represented at the 2016 AABC in a presentation given by Mei Cai of General Motors Global R&D Center. The presentation reiterated the need for advanced materials to meet the 2020 USABC goals for commercialization. Lithium metal anodes have high specific capacity (3860 mAh/g) compared to graphite ($LiC_6$ – 339 mAh/g) and silicon ($Li_{3.75}Si$ – 1860 mAh/g). Solid Power's third generation cells with an ultra-thin lithium metal anode is listed as having a specific capacity 400-500Wh/kg and an energy density of 1200Wh/L. The current development example is constructed with an ultra thin lithium "anode-free", a ceramic anode-lyte, a polymer anode-lyte, a thin cathode-lyte separator, and a cathode (also part of the cathode-lyte) of more traditional LCO, NCM, or NCA material. General Motors is currently in the process of testing that development cell which had about 225 cycles on it at the time of the presentation with some noticeable capacity fade (about 75% of the original capacity)[119]. Batteries utilizing Solid Energy's technology are apparently entering into consumer electronics as this report is being written. Solid Energy will be attempting to bring smart phone batteries into the market in 2017 and electric car batteries as early as 2018.[120]

A team consisting of 24M, Sepion Technologies, Berkeley Lab, and Carnegie Mellon University received $3.5 million as in funding from the U.S. DOE ARPA-E to develop "novel membranes and lithium-metal anodes for the next generation of high-energy-density, low-cost batteries".

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[117] USCAR, 2016. United States Council for Automotive Research, "Press Release: USABC AWARDS $7 MILLION CONTRACT TO 24M TO DEVELOP LOWER COST EV BATTERIES, MANUFACTURING PROCESS," USCAR, 27 June 2016. http://www.uscar.org/guest/news/844/Press-Release-USABC-AWARDS-7-MILLION-CONTRACT-TO-24M-TO-DEVELOP-LOWER-COST-EV-BATTERIES-MANUFACTURING-PROCESS. [Accessed 19 October 2016].
[118] PPBC, 2016. PolyPlus Battery Company, "PolyPlus in the Media," 16 September 2016. http://ppbcadmin.webfactional.com/page/news. [Accessed 19 October 2016]
[119] Cai, 2016. M. Cai, F. Dai, Y. Yang and Q. Xiao, "LITHIUM-METAL BATTERY - Application in automotive," in *Advanced Automotive Battery Conference*, Detroit, 2016.
[120] Hu, 2015. Q. Hu, "The renaissance of lithium metal: SolidEnergy's role in the future of lithium batteries," 2015. http://www.nature.com/nature/outlook/batteries/pdf/batteries.pdf. [Accessed 19 October 2016].

The funding is part of the U.S. DOE ARPA-E Integration of Novel Ion-Conducting Solids (IONICS) program that looks to accelerate solid state technology.[121]

LiS battery technology is another area that is undergoing large amounts of research in hopes developing a commercially viable product for EV applications. LiS batteries hold the promise of low cost and high specific energy. However, LiS suffers from the loss of sulfur during cycling which quickly degrades the cell. Oxis Energy, Sony, PolyPlus, Sion Power, Ilika, and Johnson Matthey are a few of the companies involved with LiS research and development.

Oxis Energy has joined a coalition of European manufacturers and research institutes on the Advanced Lithium Sulfur battery for EVs (ALISE) collaborative effort. ALISE's objective is to achieve a stable 500Wh/kg Li-S cell by 2019.[122] Oxis Energy has evaluation samples of its Long Life and Ultra Light cells available.[123,124] The company recently put out a press release claiming to have tested a development cell at over 400Wh/kg of specific energy capacity and to have cells currently being deployed for vehicle demonstration and development testing.[125]

PolyPlus Battery Company was awarded a U.S. DOE ARPA-E 36 month grant to develop low-cost, high-performance lithium-sulfur batteries in February of 2013. The company also received another U.S. DOE Advanced Manufacturing Office (AMO) grant to work with Corning Inc. and Johnson Controls Inc. to develop its Protected Lithium Electrode battery technology and manufacturing for use with Li-S, Li-Water, and Li-Air batteries. PolyPlus' PLE technology in combination with aqueous electrolytes potentially enables an energy dense and stable Li-S battery with long cycle life. In December of 2014, PolyPlus released a statement that it had constructed a 500Wh/kg primary Li-Air battery pack that was verified by scientists at the U.S. Army CERDEC.[126] The U.S. DOE AMO funding for the production project concluded at the end of August of 2015.[127] Polyplus' semi-automated pilot production line is currently being used to build and validate PolyPlus' technologies.

Advanced battery technologies beyond currently available lithium-ion could help to drive the light-duty market towards higher levels of electrification. With batteries being the dominate cost

[121] ARPA-E, 2016b. U.S. DOE ARPA-E, "IONICS," 13 September 2016. https://arpa-e.energy.gov/arpa-e-programs/ionics. [Accessed 19 October 2016].
[122] Morris, 2015. C. Morris, "European ALISE collaboration aims to commercialize lithium-sulfur batteries," Charged Electric Vehicles Magazine, 25 August 2015. https://chargedevs.com/newswire/european-alise-collaboration-aims-to-commercialize-lithium-sulfur-batteries/. [Accessed 19 October 2016].
[123] OXISE, 2016a. OXIS Energy, "Long Life Lithium Sulfur Pouch Cell," October 2016. http://oxisenergy.com/wp-content/uploads/2016/10/OXIS-Li-S-Long-Life-Cell-v4.01.pdf. [Accessed 19 October 2016].
[124] OXISE, 2016b. OXIS Energy, "Ultra Light Lithium Sulfur Pouch Cell," October 2016. [Online]. Available: http://oxisenergy.com/wp-content/uploads/2016/10/OXIS-Li-S-Ultra-Light-Cell-v4.01.pdf. [Accessed 19 October 2016].
[125] Lerwill, 2016. D. Lerwill, "OXIS Energy Advances its Lithium Sulfur (Li-S) cell technology to 400Wh/kg," OXIS Energy, 14 October 2016. http://oxisenergy.com/oxis-energy-advances-lithium-sulfur-li-s-cell-technology-400whkg/. [Accessed 19 October 2016]
[126] PPBC, 2014. PolyPlus Battery Company, "POLYPLUS LITHIUM-AIR BATTERY PACK DELIVERS 500Wh/kg," 10 December 2014. [Online]. Available: http://polyplus.com/files/2015-09/press-release-1.pdf. [Accessed 19 October 2016]
[127] Visco, 2015. S. J. Visco, "Manufacturing of Protected Lithium Electrodes for Advanced Lithium-Air, Lithium-Water & Lithium-Sulfur Batteries," in *U.S. DOE Advanced Manufacturing Office Peer Review Meeting*, Washington D.C., 2015

of PHEV and BEV powertrains, it is imperative that those costs continue to come down. Advanced battery technologies have the potential to allow for batteries that exceed the U.S. DOE goals, and bring electrified vehicles to market that are equal in cost to their conventional ICE counterparts.

### II.B.9. Well-to-Wheel (WTW) and Cradle-to-Grave (C2G) Emissions

Direct emissions from vehicle operations can be estimated and directly measured in testing (e.g., exhaust, fuel system evaporation). However, a broader evaluation of the environmental impacts of PEVs can be conducted through a "well-to-wheel" (WTW) emissions analysis, where emissions are estimated in fuel production and delivery processes, in addition to the vehicle operation. An even broader evaluation can add lifecycle stages, including vehicle manufacturing and vehicle retirement, commonly called "cradle-to-grave" (C2G) evaluations.

Both of these types of analysis typically involve estimating marginal emission factors (e.g. $gCO_2e$/mile) for varying vehicle powertrain types to compare them side-by-side. For example, an analysis could compare the WTW emission factors of a conventional combustion vehicle to an electric vehicle with today's technology. Many WTW and C2G studies also forecast how the emission factors will change with varying fuel and vehicle performance improvements over time (e.g., fuel economy improvements, renewable fuel content).

ARB conducts on-going WTW analyses as part of the Vision program,[128] and also studied it as part of the ACC rulemaking in 2012. The Vision work includes understanding emission forecasts specific to California under current policies, mobile and stationary emission inventories, and future strategies. For the ACC rulemaking environmental impact analysis, WTW emission factors were used, in addition to vehicle manufacturing emissions. The criteria emission factors for fuel production stages account for the unique, strict stationary facility emission controls in place locally to meet national air quality standards (e.g. refineries).

Probably the most widely used and cited WTW analysis tool for light-duty vehicles is ANL's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.[129] It is used for national policy development, academic research, and many independent studies. It is most robust for greenhouse gas emissions, but the criteria emission factors are national averages and do not account for local controls in varying states. ANL also studies C2G emission impacts and has recently published a study for light-duty vehicles.[130,131]

[128] ARB, 2016. California Air Resources Board. Vision Planning. June 17, 2016. https://www.arb.ca.gov/planning/vision/vision.htm
[129] ANL, 2016a, Argonne National Laboratory. "GREET 2016 Release". October 7, 2016. https://greet.es.anl.gov/
[130] Elgowainy, 2016. A. Elgowainy, et. al. "Cradle-to-Grave Lifecycle Analysis of the U.S. Light-Duty Vehicle Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025-2030) Technologies. June 1, 2016.https://greet.es.anl.gov/publication-c2g-2016-report
[131] Sullivan, 2012. JL Sullivan, et. al. "Model for the Part Manufacturing and Vehicle Assembly Component of the Vehicle Life Cycle Inventory" September 1, 2012. http://www.anl.gov/energy-systems/publication/model-part-manufacturing-and-vehicle-assembly-component-vehicle-life

ARB is familiar with additional research studies and plans to review them as part of future rulemaking efforts. This includes work by the Union of Concerned Scientists,[132] Carnegie Mellon University,[133] and UC Davis.[134] Results can vary widely based on whether the studies consider future year emission factors (vs. current year only), battery life assumptions (e.g. whether a battery is replaced during the life of the vehicle), and whether a BEV fully offsets the annual driving of a conventional car.

Nearly all WTW analyses show that ZEVs and PHEVs have lower emissions, but the fuel production emissions vary widely based on geographic location, which affects utility territories and their fuel production mix, biofuel blending with gasoline, etc. In California, where electric grid and hydrogen policies are in place to require a renewable fuel mix, WTW emissions are substantially lower for BEVs and PHEVs. When evaluating C2G emissions, batteries are more energy intensive to manufacture, so manufacturing emissions tend to be higher (but are compensated by vehicle operation emission benefits). As battery sizes increase in BEVs for driving range, vehicle manufacturing emissions per BEV also rise. Shorter range vehicles, with smaller battery packs and more frequent charging, would reduce this impact but have more limited consumer appeal. An example of the most recent light-duty vehicle WTW greenhouse gas emission analysis from the U.S. DOE is shown below in Figure 17.[135]

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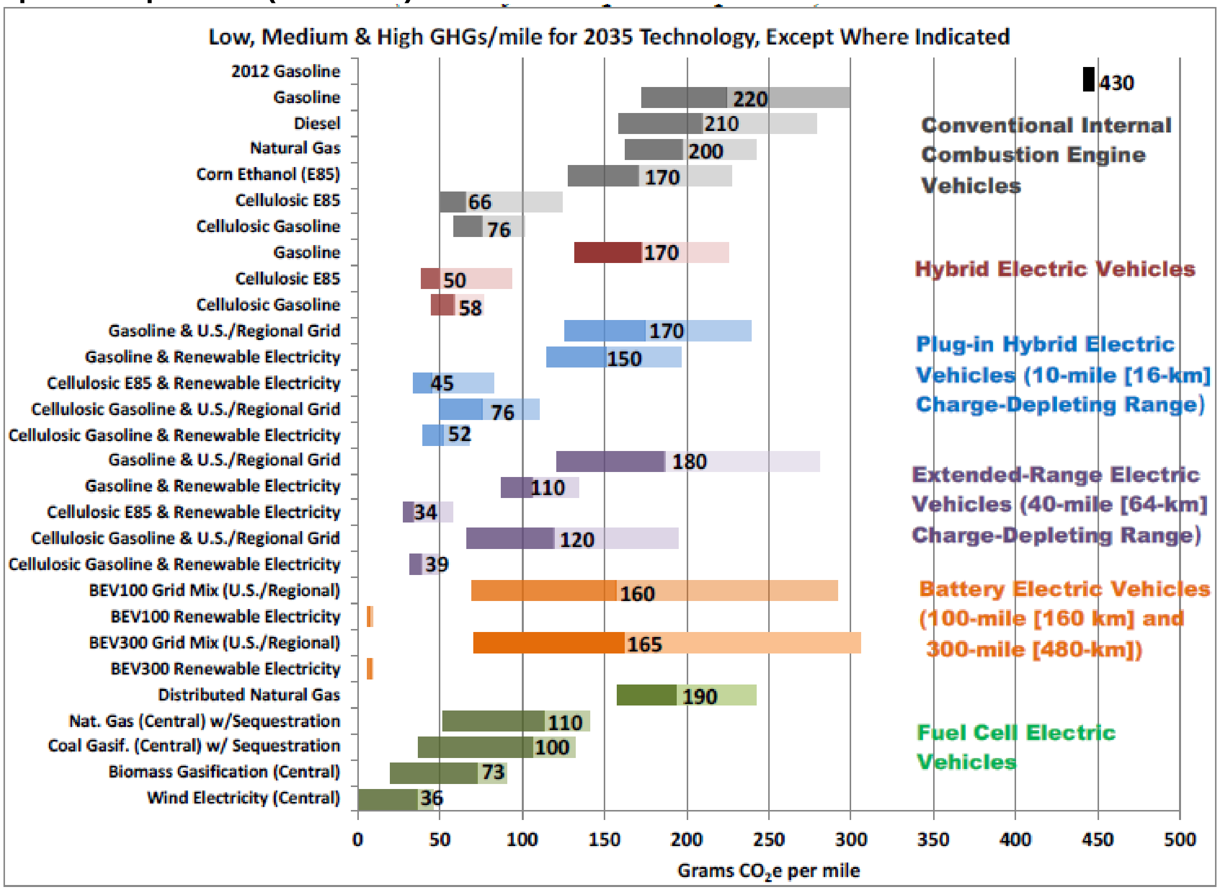
[132] UCS, 2015. Union of Concerned Scientists. “Cleaner Cars from Cradle to Grave”. November 2015. http://www.ucsusa.org/clean-vehicles/electric-vehicles/life-cycle-ev-emissions#.V-i0E7Xi7BI

[133] Moore, 2015. Tara Moore. “Carnegie Mellon Study Shows EV range and emissions vary with Climate” February 24, 2015. http://www.cmu.edu/news/stories/archives/2015/february/electric-vehicles-and-climate.html

[134] Archsmith, 2015. James Archsmith. “From Cradle to Junkyard: Assessing the Life Cycle Greenhouse Gas Benefits of Electric Vehicles” October 2015.http://www.sciencedirect.com/science/article/pii/S0739885915000517

[135] DOE, 2013b. U.S. Department of Energy, “Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles,” 10 May 2013. https://www.hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf

**Figure 17 - Well to Wheel Greenhouse Gas Emissions for 2035 Mid-Size Car, gCO2-equivalent per mile (U.S. DOE)**




*Low/medium/high: sensitivity to uncertainties associated with projected fuel economy of vehicles and selected attributes of fuels pathways, e.g., electricity credit for biofuels, electric generation mix, etc.*

### II.B.10. Battery Recycling and Reuse

Lithium-ion batteries for electric vehicles are currently expensive and represent a sizeable physical system in a vehicle (volume and mass). As a result, it is natural to consider battery recycling (to minimize waste) or battery second use (B2U) where a vehicle battery is repurposed for other uses after reaching its useful life in the car (typically defined when the battery usable energy capacity has declined to 70-75% of its original value). Currently, the value of materials in lithium-ion batteries may not be high enough to incentivize battery disassembly for recycling to recover them for secondary markets. This may change in the future as disassembly techniques evolve.  A recent study by Argonne National Laboratory explores the potential for automotive battery recycling, describing a working system to reduce processing costs.  To improve the economics of recycling, the study recommends enhancing separation technology to recover battery cells, developing greater recycling process flexibility, and where possible, standardizing battery materials and designs.[136]

[136] ANL 2014. Argonne National Laboratory. "The future of automotive lithium-ion battery recycling: Charting a sustainable course" 15 November 2014.  http://www.sciencedirect.com/science/article/pii/S2214993714000037

Using vehicle battery packs (or modules from packs) for second use has a large potential. There are many public and private parties studying B2U and the potential business opportunities. The business case for a vehicle B2U depends on the value of the competitive product, which would be new batteries specifically designed for stationary purposes. Varying use profiles and applications are being considered. This includes back-up power for buildings (e.g. warehouses, cell phone towers, etc.) or energy storage for buildings and/or the grid to supplement renewable energy. Preliminary analysis shows cost margins may be small, but there is strong potential for this to grow. Minimizing costs for removing the batteries from vehicles and repurposing them will be important. This includes identifying quick and low cost means to test the used battery's varying cells for performance and life to determine if some cells need to be repaired or replaced. Vehicle manufacturers have already begun to take steps in this direction by designing the battery pack to be able to have separately replaced modules or portions of the pack instead of the entire pack as early PEVs required.

There are many research and pilot projects being conducted around the world on B2U. In California, the U.S. DOE's National Renewable Energy Laboratory (NREL) and California Energy Commission (Energy Commission) have partnered with the Center for Sustainable Energy (CSE) and University of California San Diego.[137] Automakers are experimenting with this, including announced projects by General Motors and Nissan using Volt and Leaf batteries. BMW has been leading a study in California with the Public Utilities Commission (PUC), Integrated System Operator (ISO), and local partners.[138,139]

## II.B.11. Non-Battery Components

Non-battery components refer to anything that is not contained within the battery pack. This includes propulsion components and power electronics. Components outside of the battery pack have seen many developments since the analysis was done for the 2012 FRM. Drive motors have become smaller and more power dense, particularly in terms of volumetric power density. Inverters, OBCs, and DC-DC converters are also becoming smaller and more power dense. Substantial improvements in the design and packaging have occurred as manufacturers release second generation vehicles or expand their PEV offerings.

### *II.B.11.i. Propulsion Components*

Propulsion components for PEVs have various synonymous names including e-machines, electric machines, traction motors, motor/generators, or electric motors. For the purposes of this discussion, they will be referred to as electric motors or generators depending on contextual implementation of that motor or generator in a drivetrain, or jointly as electric machines.

[137] NREL, 2015. National Renewable Energy Laboratory. "Battery Second use for plug-in Electric Vehicles" June 26, 2015. http://www.nrel.gov/transportation/energystorage/use.html

[138] GCC, 2015b. Green Car Congress. "BMW launches BMW i ChargeForward pilot in SF Bay Area" August 4, 2015. http://www.greencarcongress.com/2015/08/20150804-bmwi.html

[139] GCC, 2016a. Green Car Congress. "Vattenfall, BMW and Bosch test second-life EV battery electricity storage in Hamburg for grid stabilization" September 23, 2016. http://www.greencarcongress.com/2016/09/20160923-bmw.html

Given their usage to date in PEVs, the focus in this assessment is mainly on permanent-magnet and induction type electric machines. Permanent-magnet electric machines are sometimes referred to as brushless direct-current (DC) motors, but both permanent-magnet and induction electric machines are powered by alternating-current (AC) on production PEVs. On-board battery packs produce DC power, so that must be converted to AC power via an on-board inverter.

The 2016 TAR provides an explanation of the two electric machine types: "In the duty cycles typical of PEV applications, permanent-magnet motors have certain advantages in energy efficiency due in part to the presence of integral permanent magnets to generate part of the magnetic field necessary for operation. However, these magnets add to manufacturing cost, particularly when they contain rare earth elements. In contrast, induction motors use copper windings to generate all of the magnetic field and can be manufactured without rare earth elements. Although the windings are significantly less costly than magnets, generation of the field in the windings is subject to additional I2R losses that are not present in permanent magnet motors. In some conditions, this causes induction motors to be slightly less energy efficient than permanent-magnet motors[140,141] although the choice between the two types of motor ultimately depends on the specific application."

[140] Schults, 2013. J. W. Schultz and S. Huard, PhD., "Comparing AC Induction with Permanent Magnet motors in hybrid," 2013. http://www.parkermotion.com/whitepages/Comparing_AC_and_PM_motors.pdf. [Accessed 4 October 2016].

[141] Widmer, 2015. J. D. Widmer, R. Martin and M. Kimiabeigi, "Electric vehicle traction motors without rare earth magnets," *Sustainable Materials and Technologies,* vol. 3, pp. 7-13, 2015.

**Table 4 - Electric Machine Type for MY16 and Known Expected MY17 ZEVs and TZEVs**[142,143]

| Manufacturer | Model | Electric Machine Type (Motor A/B) |
|---|---|---|
| Audi | A3 e-Tron | PM |
| BMW | i3 and i3 REX | PM+Reluctance |
| Cadillac | ELR | PM/PM |
| Chevrolet | Volt | PM/PM |
| Chevrolet | Spark EV | PM |
| Chevrolet | Bolt EV | PM |
| Fiat | 500e | Induction |
| Ford | Focus Electric | PM |
| Ford | C-Max & Fusion Energi | PM/PM |
| Hyundai | Sonata Plug-In Hybrid | PM |
| Kia | Soul EV | PM |
| Mercedes-Benz | B-Class Electric Drive | Induction |
| Mercedes-Benz | S550e | PM |
| Mitsubishi | i-Miev | PM |
| Nissan | Leaf | PM |
| Smart | Fortwo electric drive | PM |
| Tesla | Model S & Model X | Induction |
| Toyota | Prius Prime | PM/PM |
| Volvo | XC90 T8 | PM/PM |
| VW | e-Golf | PM |

Table 4 shows that most manufacturers are choosing permanent magnet motors for their vehicle applications. The only ZEV or PHEV other than the Tesla Model X and S, and the Mercedes-Benz B-Class Electric Drive (which uses a Tesla designed drivetrain) to use an induction electric machine is the Fiat 500e. One interesting vehicle to note is the BMW i3. It uses "a proprietary hybrid synchronous motor designed to exploit both permanent magnets and the reluctance effect."[144]

While permanent magnet electric machines generally hold an efficiency advantage over their induction counterparts, the permanent magnet electric machines require magnets. Very often, those magnets are of the rare earth variety; they contain light and heavy rare earth metals. There has been some instability in rare earth pricing in the past which impacts the cost to manufacture permanent magnet electric machines. Figure 18 shows what happened to

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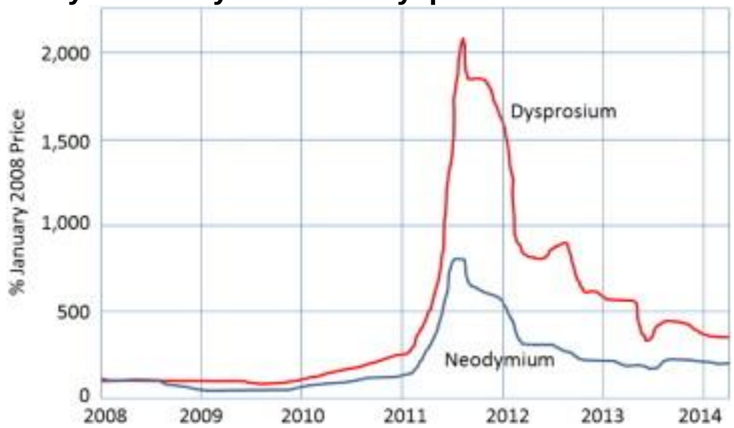
[142] Table uses data obtained from EPA online certification database (https://www3.epa.gov/otaq/cert.htm)
[143] Vaughn, 2016. Mark Vaughn. Market Watch. “Test driving the Prius Prime: The hybrid top dog goes plug in” October 17, 2016. http://www.marketwatch.com/story/test-driving-the-prius-prime-the-hybrid-top-dog-goes-plug-in-2016-10-17
[144] GCC, 2013a. Green Car Congress, "BMW’s hybrid motor design seeks to deliver high efficiency and power density with lower rare earth use," Green Car Congress, 13 April 2013. http://www.greencarcongress.com/2013/08/bmw-20130812.html. [Accessed 4 October 2016].

Neodymium and Dysprosium prices when it was reported that China threatened to stop international supply of the two materials.[145]

**Figure 18 - Price History for Neodymium and Dysprosium Rare Earth Materials[146]**




Rare earth magnets have come down in cost since China's reported supply threats, but those magnets are still understood to represent a significant portion of the costs of permanent magnet electric machines. Several manufacturers have taken steps to address the cost and cost instability issues. General Motors made a lot of changes to the second generation Chevrolet Volt powertrain to reduce rare earth metal usage in both of the drive motors. Those changes "resulted in a reduced-dysprosium-type grain boundary diffusion magnet technology for the Gen-2 Voltec's Motor B: rare-earth content dropped from 282 g (10 oz) to 40 g (1.4 oz). Motor A is rare-earth-free. It uses a General Motors proprietary ferrite multi-barrier magnet technology, developed from the ferrite magnets commonly used in high end industrial and automotive (starter motor) applications. The two new motors together reduce total rare-earth content from 3.2 kg (7 lb) on the first generation system to 1.2 kg (2.6 lb)."[147] Nissan also took steps to reduce rare earth metal usage in its Leaf powertrain. For model year 2013, as part of the Leaf's powertrain redesign, Nissan was able to reduce heavy rare metals by 40%.[148]

Honda Motor Company, Ltd. announced in July of 2016 that, in a partnership with Daido Steel, it had designed an electric machine that can utilize Daido Steel's new Neodymium magnets which are made without any heavy rare-earth metals: "Daido Electronics Co., Ltd., a wholly owned subsidiary of Daido Steel, has been mass-producing neodymium magnets using the hot deformation method, which is different from the typical sintering production method for neodymium magnets...the two companies achieved, for the first time in the world, a practical application of a neodymium magnet which contains absolutely no heavy rare earth yet has high heat resistance and high magnetic performance suitable for use in the drive motor of hybrid vehicles." The first use of this technology will be in Honda's Freed hybrid electric vehicle which

[145] Widmer, 2015.
[146] Widmer, 2015.
[147] Brooke, 2014.
[148] Nakada, 2014. T. Nakada, S. Ishikawa and S. Oki, "Development of an Electric Motor for a Newly Developed Electric Vehicle," 1 April 2014. http://papers.sae.org/2014-01-1879/. [Accessed 19 June 2014].

is only available in select Asian markets.[149] However, Daido Steel also announced in August of 2016 that it "has decided to build a neodymium magnet factory in the U.S. to meet growing demand from automakers there for motors used in hybrid and electric vehicles" indicating that vehicles in the U.S. market will likely begin utilizing its magnets.[150]

As was stated earlier, the BMW i3 utilizes a hybrid electric machine that looks like a permanent magnet motor but also utilizes reluctance effects to improve its efficiency and power density. With this approach, it is believed that BMW was able to design the motor to use less rare earth material than a conventional permanent magnet motor. It is estimated that the motor uses 1kg of magnets to produce 250Nm of torque and 125kW vs. the 2kg of magnets the Nissan Leaf's electric machine requires to produce 280Nm of torque and 80kW.[151]

Power density and efficiency of electric machines has also been trending upward in second generation products. One example of this can be seen in the improvements General Motors made between its Spark EV and Bolt EV designs. Both vehicles utilize permanent magnet motors, but the Bolt EV drivetrain is better in most ways. Peak power density has improved by over 55% and efficiency has improved as the motor can deliver 9% more maximum power with 7% less AC phase current.[152] The Volt also saw electric machine improvements from its first generation to second generation versions. "Gen 2 system motor volume was reduced by 20% vs. Gen 1 and motor mass was reduced by 40%."[153]

Current electric machines are also achieving the U.S. DRIVE targets far earlier than expected. While the cost of the motors has not been publically disclosed, both the BMW i3 and Chevrolet Bolt EV already meet the U.S. Drive targets for gravimetric power density of an electric machine by "lab year" 2020 (approximately 2025 for commercial availability). The BMW i3's motor has a maximum output of 125kW in a 50kg package that equates to 2.5kW/kg. The Chevrolet Bolt EV has achieved 150kW of peak power in a package that has a mass of 76Kg for a gravimetric power density of 1.97 kW/kg. Those improvements have resulted in both vehicles achieving very good acceleration performance numbers. BMW reports that its i3 (60Ah) BEV can do 0-60MPH in 7.0 seconds[154] and General Motors states that the Bolt EV will do it in less than 7 seconds.[155]

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[149] Honda, 2016c. Honda Motor Co., Ltd., "Daido Steel and Honda Adopt World's First Hybrid Vehicle Motor Magnet Free of Heavy Rare Earth Elements," 12 July 2016. http://world.honda.com/news/2016/4160712eng.html. [Accessed 12 October 2016]

[150] NAR, 2016. Nikkei Asian Review, "Daido Steel to make neodymium magnets in US", 26 August 2016 http://asia.nikkei.com/Business/Companies/Daido-Steel-to-make-neodymium-magnets-in-US. [Accessed 4 October 2016]

[151] Widmer, 2015.

[152] Liu, 2016.

[153] GCC, 2015c. Green Car Congress, "GM provides technical details of the Gen 2 Voltec propulsion system used in the 2016 Volt," 23 April 2015. http://www.greencarcongress.com/2015/04/20150423-voltec.html. [Accessed 14 October 2016].

[154] BMW, 2016b. BMW USA, "BMW i3," https://www.bmwusa.com/vehicles/bmwi/i3.html. [Accessed 1 November 2016]

[155] Cole, 2016. J. Cole, Inside EVs, "Chevrolet Bolt EV Specs Revealed: 60 kWh, 0-60 In "Less Than" 7 Seconds – Video," January 2016. http://insideevs.com/chevrolet-bolt-ev-specs-revealed-60-kwh-0-60-in-less-than-7-seconds/.

### *II.B.11.ii. Power Electronics*

Power electronics encompass all non-battery components that are not electric machines. Power electronics are critical to the proper functional operation of an electrified vehicle. Inverters convert DC power produced by the traction battery to the AC power required by a vehicle's electric machine(s). Most also operate as a rectifier (converting AC power to DC power) in order to capture the energy produced by the electric machine during regeneration events to put that energy back in the vehicle's battery. On-board chargers take external AC power and convert it to DC to charge the battery. DC-DC converters take the high-voltage that a vehicle's traction battery operates at and drops it down to 12 volts, or other DC voltages, for the various other vehicle accessories and systems.

#### *II.B.11.ii.1. Inverters*

Modern inverters are quite efficient at converting AC power to DC power with most achieving efficiencies above 90 percent over a wide range of operating conditions. Currently, inverters use insulated-gate bipolar transistors (IGBT) or metal-oxide-semiconductor field effect transistors (MOSFET) to achieve those efficiencies. High powered inverters also generate a lot of heat which generally requires liquid cooling to keep operating temperatures in check. PHEVs compound the temperature problem, as the packaging constraints usually require the inverter to be placed underneath the hood with the internal combustion engine.

Manufacturers are already finding new and better ways to package inverters and other power electronics. The first generation Chevrolet Volt integrated most of the power electronics into a module that General Motors refers to as the Traction Power Inverter Module (TPIM).[156] The second generation Volt had many improvements made to the TPIM. Total simultaneous power capability of the new TPIM was reduced from 221kVA to 180kVA, but power density improved by 43% (kVA/Kg). Volume of the module improved from 13.1L to 10.4L and mass was also reduced by over 43% from 14.6Kg to 8.3Kg. Some of the improvements to the revised TPIM can be attributed to the integration of the TPIM with the transaxle housing. This enabled the replacement of the six large 3-phase AC motor power cables with less expensive and lower mass rigid buss bars.[157] Another source of the improvements comes from Delphi's Viper double sided cooled IGBT system. The novel design package was presented by Delphi at EVS26 in 2012. Delphi stated that "The new packages provide low electrical and thermal impedances, can be tested individually, and also provide the capability for double sided cooling. Due to their unique design, these packages enable higher and more uniform current densities. Combined with matching coefficient of thermal expansion, this design provides for a highly reliable component that can also be easily manufactured using standard low-cost, high volume manufacturing processes."[158]

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[156] Rahman, 2011. K. Rahman, et.al. "The Voltec 4ET50 Electric Drive System," *SAE Int. J. Engines,* vol. 4, no. 1, pp. 323-337, 2011.

[157] Anwar, 2015. M. Anwar, et. al. "Power Dense and Robust Traction Power Inverter for the Second-Generation," Journal of Alternative Powertrains, vol. 4, no. 1, pp. 145-152, May 2015.

[158] Cameron, 2012. G. Cameron, M. Hayes, H. Lee and R. Taylor, "New Developments in Power Electronics," in *EVS26*, Los Angeles, 2012

Another example of advancements made to power electronics modules can be seen in the improvements made by Toyota from the third to fourth generation Prius. While the Prius is a conventional hybrid, it is likely that the improvements made to the conventional hybrid will also be implemented in the model year 2017 Prius Prime PHEV; the Prime has the same motor/generator powertrain as the conventional Prius except with the addition of a one way clutch to use both motors to provide motive power. Toyota reduced the volume of what they call the power control unit (PCU) from 12.6L to 8.2L; a reduction of about 35%.[159] The volume reduction was in due in some part to a similar advancement utilized by the second generation Chevrolet Volt TPIM, smaller IGBTs enabled by double sided cooling. Toyota was also able to reduce losses from the IGBTs by about 20%. Increasing the efficiency of inverters can allow manufacturers to reduce battery pack energy capacities which reduce costs of the vehicle, or increase range for the same capacity battery pack. The volume and mass reductions also increase overall vehicle efficiency and provide for better packaging opportunities.

### *II.B.11.ii.2. On-Board Chargers*

OBCs have also increased in efficiency and power capability since the 2012 ACC rulemaking. Nissan debuted the Leaf with a 3.6kW OBC but added an upgrade to a 6.6kW OBC by the 2013 model year. Chevrolet introduced the Spark EV with a 3.3kW OBC but will equip the Bolt EV with a 7.2kW OBC.[160] The BMW i3 came with a 7.2kW OBC in its introductory model year but is receiving an updated charger next year that can take up to 32A, and in markets where 3-phase AC power can be supplied, the new OBC can accept up to 11kW of power.[161] The Tesla Model S in 2012 came standard with a 10kW charger. Tesla has offered an option to customers for a 20kW system which utilized two of the 10kW OBCs (using 80amps at 240V). Tesla introduced a new 48A (11.5kW) OBC with the Model X and then made that OBC standard on the Model S in 2016 when the vehicle received a facelift.[162] An optional 72A OBC was made available sometime after the Model X was introduced and on the Model S after the facelift.[163] The 72A OBC appears to be a single unit, exceeding the original 40A unit in power capability by 80%.

PHEVs are also receiving more powerful OBCs. General Motors brought the first generation Chevrolet Volt to market with an OBC that was capable of 3.3kW. The OBC was updated on the second generation Volt to charge the battery at 3.6kW.[164] Porsche has also increased the power capability of the OBCs on its PHEV products. The company added an optional 7.2kW OBC on its Cayenne E-Hybrid[165] and made the same option available on the forthcoming Panamera 4 E-

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[159] Nezu, 2015. T. Nezu, Nikkei Technology. "PCU Volume Reduced by 33% for New Prius,", 16 October 2015. http://techon.nikkeibp.co.jp/atclen/news_en/15mk/101500104/?P=1. [Accessed 14 October 2016].
[160] Liu, 2016.
[161]BMW, 2016c. BMWi, "DESTINATION WITHIN RANGE. PLENTY OF ENERGY LEFT. Ideal for everyday use - range and charging for the BMW i3,".http://www.bmw.com/com/en/newvehicles/i/i3/2016/showroom/range_charging.html. [Accessed 14 October 2016]
[162] Kierstein, 2016. A. Kierstein, "Tesla Model S finally gets a facelift," Autoblog, 12 April 2016. http://www.autoblog.com/2016/04/12/tesla-model-s-finally-gets-a-facelift/. [Accessed 14 October 2016]
[163] Tesla, 2016b. Tesla Motors, "Model X," 2016. https://www.tesla.com/modelx/design. [Accessed 14 October 2016]
[164]Cesiel, 2016. D. Cesiel and C. Zhu, SAE International. “Next Generation “Voltec” Charging System”, April 5, 2016.
[165] PCNA, 2016. Porsche Cars North America, Inc., "Porsche E-Performance," Porsche Cars North America, Inc., 2016. http://www.porsche.com/usa/models/cayenne/cayenne-s-e-hybrid/drive/e-performance/. [Accessed 17 October 2016]

Hybrid[166] in addition to the originally offered 3.6kW units. The higher powered units give customers the opportunity to charge their vehicles in less time for a similar capacity battery pack or to allow for inclusion of larger capacity packs without increasing charging time.

Physical volume of OBCs has also trended downward. The Chevrolet Bolt OBC at 12.3L is smaller in volume than the Chevrolet Spark EV OBC at 13.0L. This decrease in volume happened despite the fact that the Bolt EV OBC can handle more than twice the power; 7.2kW vs. 3.3kW. Mass is up on the Bolt EV OBC, 12.0Kg vs. 9.3Kg, but the gravimetric energy density is up by 69%. The Spark EV OBC has a power density of 354 W/Kg while the Bolt EV has a power density of 600 W/kg.[167] Increasing the power density of OBCs gives the manufacturer more flexibility to place and package it on the vehicle, potentially giving the customer more space or other benefits.

Efficiencies of OBCs are increasing as well. While changes in efficiency may not result in differences on the range of the vehicle, they do affect the wall to wheel efficiency of the vehicle and the “miles per gallon gasoline equivalent” rating that is reported on the label. Idaho National Lab’s Advanced Vehicle Testing group has tested several chargers on vehicles under various input power conditions. Table 5 shows the results of that testing on the various vehicles. General Motors has reported that the OBC on the 2016 Volt is 93% efficient using level 1 charging, and 95% efficient when using level 2. INL did not have its own testing results for the 2016 Volt, but General Motors’ results would make the new Volt OBC more efficient than anything that INL has tested and reported results for.[168]

**Table 5 - INL OBC Testing Results of Several Vehicles[169]**

| Make | Model | MY | L1 Max Power (kW)/ Eff (%) | L2 208V Max Power(kW)/ Eff (%) | L2 240V Max Power (kW)/ Eff (%) |
|---|---|---|---|---|---|
| Chevrolet | Volt | 2012 | 1.38 / (86.6) | 3.14 / (88.5) | - |
| Nissan | Leaf | 2012 | 1.38 / (86.4) | 3.71 / (88.7) | - |
| BMW | i3 | 2014 | 1.33 / (89.6) | 6.47 / (93.4) | 7.22 / (93.8) |
| Nissan | Leaf | 2015 | 1.38 / (78.4) | 6.16 / (90.5) | - |
| Mercedes | B-Class EV | 2015 | 1.38 / (84.7) | - | 7.10 / (91.4) |

## II.B.12. Non-Battery Components Expected Developments

Components outside of battery packs have also been moving along at an impressive pace. Electric machines will continue to get more powerful and power dense, while improving drive efficiency and lowering costs. Manufacturers are, and will be, installing higher power OBCs on vehicles to enable faster battery recharge times. New wide bandgap SiC material technology is currently coming to market and will enable more efficient and power dense power electronics with the potential for lowering cost.

166 Korzeniewski, 2016
167 Liu, 2016
168 INL, 2013. Idaho National Labs, "2013 Chevrolet Volt | Advanced Vehicle Testing Activity," https://avt.inl.gov/sites/default/files/pdf/phev/fact2013chevroletvolt.pdf. [Accessed 29 September 2016].
169 INL, 2014. Idaho National Labs | Advanced Vehicle Testing Activity, "2014 BMW i3," 10 May 2016. https://avt.inl.gov/sites/default/files/pdf/fsev/fact2014bmwi3ev.pdf. [Accessed 29 September 2016].

### *II.B.12.i. Propulsion Components Expected Developments*

Suppliers and OEMs continue to make progress towards the U.S. DOE EV Everywhere targets. In the case of electric machines, many have already reached the U.S. Drive 2020 lab year goals for power density on production vehicles. Electric motors in vehicles like the BMW i3 and the Chevrolet Bolt EV have already achieved specific power ratings well above the U.S. DOE targets. The challenge will be in hitting the specific power targets at the cost targets. Most OEMs are using permanent magnet electric machines despite their need to use expensive magnets. But, several OEMs have already shown products with large reductions in rare earth metal usage. This appears to be the trend into the near future due to the efficiency advantages of permanent magnet electric machines over their inductive counterparts. Higher efficiency electric machines require smaller overall batteries and are very attractive given the high cost of batteries. Those lower costs will help to bring vehicle prices down relative to conventional ICE vehicles.

During meetings with OEMs, several indicated that they are working with suppliers to continue to remove rare earth metals from their electric machines. The motivation to do so is centered on reducing cost and risk of cost fluctuations. Collaborative efforts like the previously mentioned work between Honda and Daido Steel will likely take place between other OEMs and suppliers. Daido Steel's new U.S. neodymium magnet factory is expected to come online in 2019 and should help to provide the market with more magnetic components for future electric machines.

OEMs are, for the most part, keeping electric machine development in house. However, there are some suppliers that have already brought, or will bring, electrified propulsion products to market. YASA Motors offers a line of electric machines based on axial flux technology. YASA's electric machines exhibit very high power densities; as high as 10kW/kg in some cases with peak efficiency of up to 96%.[170] The specific power is well above the U.S. DOE targets but the cost of YASA's products has not been publically disclosed.

Electrified axle assemblies have the ability to enable all-wheel drive (AWD) on PHEVs without any mechanical connection between the electrified transaxle and the ICE drivetrain. Volvo has already implemented the GKN eAxle in the XC90 T8, and will have the same electric AWD on its forthcoming S90 and V90 T8 models. Suppliers are beginning to come to market with fully integrated electrified transaxle solutions as well. GKN, Xtrac, and ZF all have forthcoming products. GKN announced its e-Twinster electrified axle based on the Twinster unit currently used in the Ford Focus RS that is capable of torque vectoring (the ability to direct torque to either side of the vehicle that helps enhance a vehicle's driving dynamics).[171] The eDrive Twinster is rated at 60 kW and 240 Nm with a maximum speed of 13,000 rpm.[172] YASA Motors has partnered with Xtrac to create the P1227 Integrated Lightweight Electric Vehicle transmission line (ILEV). The configurable gearboxes can be used in various configurations

[170] YASA, 2016a. YASA Motors, "http://www.yasamotors.com/technology/," 2016. http://www.yasamotors.com/technology/. [Accessed 14 October 2016]

[171] GKN, 2015. GKN PLC, "GKN supplies innovative AWD system to Ford Focus RS," 14 September 2015 http://www.gkn.com/frankfurt/news-and-Media/Pages/GKN-supplies-innovative-AWD-system-to-Ford-Focus-RS.aspx. [Accessed 14 October 2016]

[172] GKN, 2016. GKN PLC, "Advanced eDrive TWINSTER," GKN Driveline, http://www.gkn.com/frankfurt/technology-and-solutions/future/Documents/Advanced%20eDrive%20Twinster%20en.pdf. [Accessed 14 October 2016].

such as an integrated electrified axle solution similar to GKN's. The ILEV, when used in place of a differential, can be configured with two YASA motors to provide up to 3,900 Nm of torque and 320 kW at the wheels in a 95 kg package for a specific power of 3.37 kW/kg, not including power electronics.[173] ZF announced its electric axle drive at the beginning of 2016 and stated that it will go into volume production in 2018. The ZF unit uses an induction motor to produce up to 150 kW and 380 Nm in torque which can result in up to 3,500 Nm of torque at the axle. It is a fully integrated design which includes the power electronics with a total mass of 113 kg and a specific power of 1.32 kW/kg which is very close to the U.S. DOE EV Everywhere goal for a combined motor and power electronics package.[174]

Another development that is likely to find its way into blended power-split PHEVs is the use of a one way clutch on the electric machines that are usually designated to generate electric power from the ICE rather than power the wheels. Both the 2017MY Prius Prime and Chrysler Pacifica Hybrid PHEVs are using such a device. "For the first time in a Toyota hybrid, the system uses a "dual motor drive."… a new one-way clutch engages both the generator (MG1) and electric drive motor (MG2) for drive force, the first time MG1 has been used for that purpose."[175] The Chrysler Pacifica Hybrid does the same thing to expand that power capability of the electrified portion of the powertrain.[176] The vehicles can then provide customers with a more electric experience on a power-split system without increasing costs significantly.

### *II.B.12.ii. Power Electronics Expected Developments*

Manufacturers are continuing to make progress towards the U.S. Drive and EV Everywhere goals for not just propulsion components, but power electronics as well. Double sided cooling of IGBTs and related components that debuted in both the newest versions of the Chevrolet Volt and Toyota Prius likely represent where the industry is headed when it comes to inverter packaging and design in the very near future. Hitachi has shown that for the same chip size, an increase of up to 30% in current was possible with double sided vs. singled sided cooling.[177] Some of the OEMs that staff met with indicated that the DOE target for motor and power electronics should be achievable for the combination of motor and inverter. The developments allow for smaller designs and more efficient thermal management which can lower costs and provide for more flexible packaging of those components on a vehicle.

Some other interesting developments were shown at DOE's 2016 Annual Merit Review. General Motors presented on a U.S. DOE co-funded project to develop a next generation inverter capable of 55kW of peak power and 30kW of continuous power. The project identified the DOE

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[173] YASA, 2016b. YASA Motors, "P400 Series with Lightweight Gearbox," YASA Motors, 26 July 2016. [Online]. Available: http://www.yasamotors.com/p400-with-lightweight-gearbox/. [Accessed 14 October 2016]

[174] Friedrichshafen, 2016. ZF Friedrichshafen AG, "ZF's Electric Axle Drive to Enter Volume Production in 20183 January 2016. https://www.zf.com/corporate/en_de/press/list/release/release_18319.html. [Accessed 14 October 2016].

[175] GCC, 2016b. Green Car Congress, "Prius Prime PHEV pricing to start at $27,100; on sale later this year," 7 October 2016. http://www.greencarcongress.com/2016/10/20161007-prius.html. [Accessed 14 October 2016]

[176] Chrysler, 2016. Chrysler Group, LLC. "Introducing the 2017 Chrysler Pacifica Hybrid, the first hybrid minivan," 1 September 2016. https://blog.chrysler.com/vehicles/pacifica/introducing-2017-chrysler-pacifica-hybrid-first-hybrid-minivan/. [Accessed 14 October 2016]

[177] Kimura, 2014. Takashi Kimura, Hitachi Review. "High-power-density inverter technology for hybrid and electric vehicle applications" 2014. http://www.hitachi.com/rev/pdf/2014/r2014_02_106.pdf

targets of $3.30/kW at a volume of 100,000 units with a power density of 13.4 kW/l, specific power of 14.1 kW/kg and efficiency of over 94% for 10-100% speed at 20% rated torque. The prototype device met the U.S. Drive 2020 power density target and is expected to meet the cost target when the design is scaled up to higher power levels. To meet automotive reliability requirements and bring a scaled up device into production, the substrate attachment process would need further refinement.[178]

Vehicle OBCs will also continue to improve and increase in power. The updated BMW i3 (94Ah) will have an OBC that can utilize 3 phase AC electricity to extend its peak power capability to 11kW.[179] The Chrysler Pacifica Hybrid will have a unit capable of 6.6kW.[180] Several OEMs showed staff confidential plans that involved increasing on-board charger capability that went hand in hand with range increases as new products come to market, or are going through a refresh. These improvements lead to the potential for consumers to recharge their vehicles in less time with supporting infrastructure.

In order to meet the DOE EV Everywhere performance and cost targets for power electronics, several entities have been developing wide bandgap materials to replace silicon (Si) in switching electronics. Wide bandgap refers to the amount of "energy required for an electron to jump from the top of the valence band to the bottom of the conduction band within the semiconductor. Materials which require energies typically larger than one or two electronvolts (eV) are referred to as wide bandgap materials."[181] Two materials, Silicon Carbide (SiC) and Gallium Nitride (GaN) show great promise for RF power and switching applications. GaN lends itself better to higher frequency applications due to its higher electron mobility and electron saturation velocity. SiC has lower electron mobility and saturation velocity than GaN, but its thermal conductivity is much higher, lending itself to be better in high power density applications.[182]

Several DOE research and development projects have been ongoing to prove that wideband technology is viable. One such project was awarded to Cree, Inc. and began in December of 2014. Cree has subsequently spun off its Power and RF division into a new company, Wolfspeed, which Infineon has agreed to purchase.[183,184] The project has set out to develop

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[178] Zhao, 2016. Z. Zhao, "Next Generation Inverter - Project ID #EDT040," in 2016 Annual Merit Review, Washington D.C., 2016
[179] BMW, 2016c.
[180] Halvorson, 2016. B. Halvorson, Green Car Reports "2017 Chrysler Pacifica Hybrid: More Details On 30-Mile Plug-In,", 20 January 2016. http://www.greencarreports.com/news/1101960_2017-chrysler-pacifica-hybrid-more-details-on-30-mile-plug-in. [Accessed 17 October 2016]
[181] MPPG, 2014. Microsemi PPG, "Gallium Nitride (GaN) versus Silicon Carbide (SiC) In The High Frequency (RF) and Power Switching Applications," 2014. https://www.digikey.com/Web%20Export/Supplier%20Content/Microsemi_278/PDF/Microsemi_GalliumNitride_VS_SiliconCarbide.pdf. [Accessed 17 October 2016]
[182] MPPG, 2014.
[183] CI, 2015. Cree, Inc., "Cree Announces Wolfspeed – the New Name for the Power and RF Business," 2 September 2015. http://www.cree.com/News-and-Events/Cree-News/Press-Releases/2015/September/Cree-Power-and-RF-is-now-Wolfspeed. [Accessed 17 Octoberr 2016]
[184] ITAG, 2016. Infineon Technologies, AG, "Infineon to acquire Wolfspeed for US Dollar 850 million in cash," Infineon Technologies, AG, 14 July 2016. [Online]. Available: http://www.infineon.com/cms/en/about-infineon/press/press-releases/2016/INFXX201607-071.html. [Accessed 17 October 2016]

Automotive Electronics Council (AEC) Q101 -001-006[185] qualified 900V SiC MOSFETs that could then be incorporated into a 88kW automotive inverter with the goal of meeting or exceeding the DOE targets on cost and performance. The MOSFETs have been proven and sampled, and the project is currently working on implementing the MOSFETs in an inverter for PEVs to benchmark and compare to existing technologies. A modeling tool was used to predict inverter losses across the EPA 2-cycle tests. The model assumed a Ford Focus EV with a 90kW internal permanent magnet motor coupled with either a C-Max 90kW Si IGBT inverter or the Wolfspeed 88kW SiC inverter. Results of the modeling showed that SiC reduced inverter losses by 67% across the combined EPA drive cycle compared to the Si inverter.[186] Cost is still somewhat of an issue due to low yields on relatively small wafer fabs, but as wafer sizes and yields increase, cost of the technology should come down.[187]

Another U.S. DOE funded research project was awarded to Delta Electronics to develop a GaN-based bidirectional 6.6kW OBC for PEVs. The program goals for the OBC included a design that would operate at 95% efficiency, provide a 30% to 50% improvement in power density over other benchmark designs (0.45 to 0.75 kW/L), and be capable of a switching frequency range of 0.3-1MHz. The project, so far, has shown a prototype part that achieved a total system efficiency of over 96% from 280 to 420V to the battery. The project is expected to finish in FY17 after which Delta is looking to create a commercialization plan to bring such a product to market, but it is unclear as to when that may happen.[188] Toyota has started on-road testing of SiC technology in a fleet of hybrid Camrys and a fuel cell bus.[189] SiC based power electronics have allowed Toyota to significantly reduce the volume of the PCU on its vehicles. Toyota displayed the result of those prototype design efforts in 2014 which can be seen in Figure 19. The goal of the project is to gather data on performance of the SiC equipped boost converter and drive motor inverter to further the development of the technology and bring it to market it as soon as possible.

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185 AEC, 2016. Automotive Electronics Council, "AEC-Q101 -001-006," http://www.aecouncil.com/AECDocuments.html. [Accessed 17 October 2016]

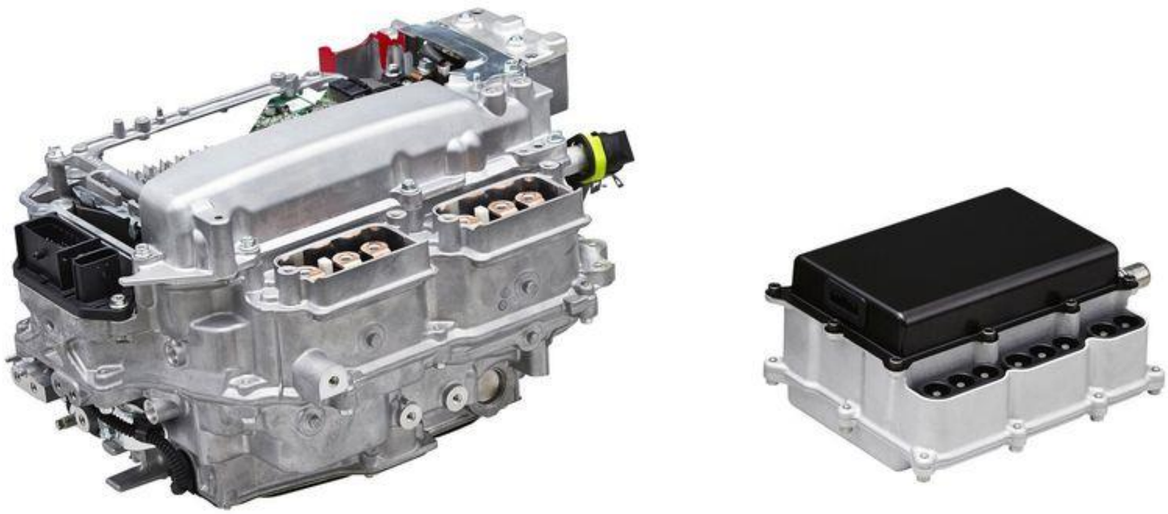
186 Casady, 2016. J. Casady, et. al., "Cree, Inc., EE0006920 "88 Kilowatt Automotive Inverter with New 900 Volt Silicon Carbide MOSFET Technology"," in 2016 U.S. Department of Energy

187 Davis, 2011. S. Davis, PowerElectronics.com "1200V SiC MOSFET Poised to Replace Si MOSFETs and IGBTs," 1 February 2011. http://powerelectronics.com/discrete-power-semis/1200v-sic-mosfet-poised-replace-si-mosfets-and-igbts. [Accessed 17 October 2016].

188 Zhu, 2016. D. C. Zhu, "High-Efficiency High-Density GaN-Based 6.6kW Bidirectional On-board Charger for PEVs," in 2016 U.S. Department of Energy Annual Merit Review, Washington D.C., June 8, 2016. https://energy.gov/sites/prod/files/2016/06/f32/edt067_zhu_2016_o_web.pdf

189 GCC, 2015d. Green Car Congress, "Toyota beginning on-road testing of new SiC power semiconductor technology; hybrid Camry and fuel cell bus", 29 January 2015. http://www.greencarcongress.com/2015/01/20150129-toyotasic.html. [Accessed 17 October 2016].

**Figure 19 - Toyota Production PCU (left) and SiC Prototype PCU (right)[190]**



During staff's meetings with OEMs, several OEMs indicated that SiC appeared to be a viable technology for MY2020 and later vehicles. Some of the delay in market introduction is due to current cost constraints of the material that stem from low yields during material creation. The likely initial applications for SiC technology will be traction drive inverters. OEMs also indicated that they did not see GaN as being cost viable until closer to 2025CY where the technology will most likely be used in devices like OBCs where higher frequency switching capability is more important than power capability.

## II.B.13. Other Expected Developments

There are currently three DCFC standards available in the U.S. for customer use. Two of the three, SAE J1772 Combo Connector System (SAE CCS) and CHAdeMO standards, are essentially limited to 50kW of power delivery to the vehicle. The third, Tesla's proprietary standard and connector, is capable of delivering up to 145kW of charging power on its Supercharger network which it created to "to remove a barrier to the broader adoption of electric vehicles..."[191] At this point in time, Tesla indicates that it only allows its vehicles to charge at a rate of 120kW.[192] However, there has been quite a lot of movement towards developing higher powered fast charging standards. Those higher power standards have implications for equipment on a vehicle, as the battery pack and supporting hardware must be able to support those higher power charging rates.

The CHAdeMO Association announced in June of 2016 that it plans to release an amendment to its standard that will enable charging rates of up to 150kW. The higher charge rate

[190] GCC, 2014b. Green Car Congress, "Toyota and Denso develop SiC power semiconductor for power control units; targeting 10% improvement in hybrid fuel efficiency," 20 May 2014. http://www.greencarcongress.com/2014/05/20140520-sic.html. [Accessed 17 October 2016]

[191] Tesla, 2015. Tesla Motors. United States Securities Exchange Commission. "Tesla Letter to SEC re:Tesla Motors, Inc. Form 10-K for Fiscal Year Ended December 31, 2013," 22 January 2015. https://www.sec.gov/Archives/edgar/data/1318605/000119312515017866/filename1.htm [Accessed 31 October 2016]

[192] King, 2016. D. King, Autoblog "Tesla boosts Superchargers to 145 kW, backs 'fastest' claim," 22 July 2016. http://www.autoblog.com/2016/07/22/tesla-supercharger-145-kw-fastest/. [Accessed 17 October 2016]

amendment specifically states that the plug will remain the same, allowing current vehicles that utilize CHAdeMO DCFC to use the new 150kW capable infrastructure installations. The press release also stated that the CHAdeMO Association was in the process of conducting a 350kW (1000V x 350A) technical study in anticipation of future market demand.[193]

The Charging Interface Initiative Association (CharIN) was formed in 2015 in part to develop the Combined Charging Standard (CCS) which the SAE Combo connector is part of. CharIN is working with an impressive set of members including automakers, infrastructure suppliers, and service providers to set standards for 150kW in the near term and up to 350kW in the not too distant future. At the 2015 Electronics in Vehicles (ELIV) conference in Germany, the CharIN group displayed charging equipment and vehicles capable of charging at 150kW.[194]

In July of 2016, the Obama Administration announced several federal and private sector actions to accelerate EV adoption in the U.S. One of those actions included conducting a study to explore the feasibility of 350kW charging for EVs. The U.S. DOE in partnership with industry members, NREL, and other stakeholders will research the vehicle, battery, infrastructure, and economic implications of 350kW DCFC.[195] The charging equipment appears to be feasible, as ITT Cannon recently announced that they will be introducing next-gen DCFC equipment at eCarTec 2016 which has been tested to 400A at 1000V (400kW). The design includes a liquid-cooled connector and cable that enables high current throughput in a manageable size cable.[196] However, batteries may not quite be ready for the demands that charging at 350kW would place on them. Porsche, with its 800V battery system technology is poised to best take advantage of the higher charging rate, but in a presentation at the 2016 AABC, Dr. Christian Jung showed that the fastest the vehicle can charge at is 225kW due to limitations of the battery cells themselves.[197] It is unclear whether there is time to adjust cell parameters for the vehicle by its market introduction to allow the vehicle to charge at rates faster than 225kW. As battery technology continues to develop, charge acceptance is set to increase which will allow future battery packs to take advantage of charging power rates closer to the 350kW target. Consumers will be able to charge at faster rates and minimize down time from refueling using the high powered infrastructure.

DCFC technology is not the only charging sector undergoing accelerated development. Barney Carlson from INL gave a presentation at ARB's 2016 Advanced Clean Cars Symposium entitled "Wireless Charging for Electric Vehicles: INL's Testing Supports Code & Standards Development". INL is currently testing and developing wireless charging equipment to develop

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[193] CAE, 2016. CHAdeMO Association Europe, "CHAdeMO ANNOUNCES HIGH POWER (150KW) VERSION OF THE PROTOCOL," 1 June 2016. http://www.chademo.com/wp/wp-content/uploads/2016/06/2016-06-01_High_power_CHAdeMO.pdf. [Accessed 17 October 2016]
[194] GCC, 2015e. Green Car Congress, "ABB joins CharIN; taking Combined Charging System to the next level; 150 kW demos, targeting 350 kW," Green Car Congress, 22 November 2015. http://www.greencarcongress.com/2015/11/20151122-charin.html. [Accessed 17 October 2016]
[195] Nakada, 2014.
[196] GCC, 2016c. Green Car Congress, "ITT introducing next-gen ultra-fast DC charging system; tested 400A at 1000V", 12 October 2016. http://www.greencarcongress.com/2016/10/20161012-itt.html. [Accessed 17 October 2016
[197] Jung, 2016. P. Christian Jung, "The Future of EVs and Fast Charging at 800V," in Advanced Automotive Battery Conference, Detroit, 2016

SAE's wireless charging standard SAE TIR J2954.[198] The technical information report (TIR) calls out two different power levels identified and the press release adds two more potential power levels for future revisions of the work in progress (WIP) standard. Those power levels can be seen in Table 6. Wireless power transfer (WPT) equipment will begin rollouts on commercial vehicles starting with the 2017MY Mercedes-Benz S550e PHEV. The system on the S550e will use Qualcomm's Halo technology to wirelessly transfer power at up to 3.6kW with an efficiency of 90% relative to a conductive system of the same power level.[199] Several OEMs indicated that they would begin to roll-out WPT systems on vehicles between the 2018 and 2020MY. WPT systems may have strong potential for autonomous vehicle charging that could have significant impacts on BEV and PHEV markets in the future.

**Table 6- SAE TIR J2954 and Future Potential Power Levels**

| Power Level Name | Power (kW) | Standard |
|---|---|---|
| WPT 1 | 3.7 | TIR J2954 |
| WPT 2 | 7.7 | TIR J2954 |
| WPT 3 | 11 | Future Revision of J2954 |
| WPT 4 | 22 | Future Revision of J2954 |

A few OEMs have announced plans for dedicated or flexible vehicle platforms that are designed with electrification in mind from the outset. The flexible platform allows for better integration of batteries, motors, and power electronics without requiring the vehicle model to be dedicated to the powertrain. Volvo has designed two such flexible platforms, Scalable Platform Architecture (SPA) and Compact Modular Architecture (CMA). SPA is currently in use with the XC90 and will underpin the soon to be released S90 and V90 vehicles, allowing them to simply incorporate the AWD T8 PHEV engine package from the XC90. The smaller platform, CMA, will be used in a similar manner on smaller vehicles. CMA is expected to debut in 2017 and will have a PHEV engine option (T5) that can be offered in any vehicle riding on the CMA platform.[200]

Dedicated electrified platforms may debut in the near term. Currently, Tesla is the only manufacturer that offers a dedicated pure BEV electrified platform that is used for more than one vehicle model. Volkswagen has announced a flexible, EV only platform, that the company calls its Modular Electric Drive kit (MEB). The MEB platform will play a major role in bringing the over 30 pure-electric vehicles to market by 2025 as laid out in VW's Strategy 2025 plan.[201] The platform will allow VW to do away with the costs and complexities of converting an ICE based platform to utilize a BEV powertrain. Additionally, it will allow for engineers and designers to take

[198] Carlson, 2016. B. Carlson, "Wireless Chargiing for Electric Vehicles: INL's Testing Supports Code & Standards Development," in Advanced Cleen Cars Symposium: The Road Ahead, Diamond Bar, 2016 https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/wireless_charging_richard_carlson.pdf

[199] GCC, 2016d. Green Car Congress, "2017 Mercedes-Benz S550e PHEV will offer wireless charging system built using Qualcomm Halo inventions," 11 October 2016. http://www.greencarcongress.com/2016/10/2017-mercedes-benz-s550e-phev-will-offer-wireless-charging-system-built-using-qualcomm-halo-inventio.html. [Accessed 17 October 2016]

[200] Gluckman, 2016. D. Gluckman, Autoblog "10 things you should know about Volvo's new compact cars," 19 May 2016. http://www.autoblog.com/2016/05/19/volvo-new-compact-cars-10-things-featured/. [Accessed 17 October 2016]

[201] VW 2016

advantage of the opportunities presented with the more compact drive motors used by BEVs and lack of need for emissions equipment.

### II.B.14. Potential Long-Term Developments in Non-Battery Components

Developments to non-battery components to the medium and long term are more difficult to assess. Based on information gathered from meetings with OEMs, the focus will be on reducing costs. That is likely to include continued focus on removing rare-earth metals from electric machines and any associated componentry. OEMs and suppliers will continue to push towards more specific power and power dense electric machines to meet the U.S. DOE EV Everywhere targets. Doing so will result in smaller, lighter, more powerful electric machines which will enable more capable vehicles in a wider variety of platforms and implementations.

Power electronics are expected to see a continued push towards more efficient, lower cost designs. SiC based systems will likely see continued development to further improve efficiency and that will meet the U.S. DOE EV Everywhere goals. GaN materials may become viable closer to 2025 which will allow smaller and even more efficient OBCs. Some OEMs indicated that their PHEVs will come with progressively higher powered OBCs. GaN will be important in making sure that OBCs do not grow in size proportional to their power capability increase. The potential for high levels of efficiency with GaN could help to lower well to wheel emissions, decrease charge times, and decrease the cost to refill the battery because a higher portion of the power would be transferred from the wall to the vehicle's battery pack rather than lost through inefficiencies.

### II.B.15. Potential Long-Term Developments in Charging Technology

Longer term will likely see the proliferation of 350kW DCFC if initial rollouts of the infrastructure take place successfully. As was discussed in II.B.13, Porsche has reported that it doesn't expect its Mission E vehicle to be fully capable of 350kW charging with the battery technology that is slated to be on the vehicle when it debuts on the market. As battery technology improves to allow higher charging rates, vehicles will be able to accept increasing amounts of charging power closer to the 350kW rate. It is also likely that vehicles will have to move to higher voltage battery packs, like the Porsche 800V design. Charging cord wire diameter, and mass, is directly proportional to its current carrying ability. Without a major advance in cable cooling or material technology, reasonably sized charge cables will be limited to about 350A in current capability. Levels beyond 350A would result in the cable being too heavy and bulky for people to use. CHAdeMO, in the announcement about its amendment for 150kW, called out a potential future 350kW standard from them as 350A at 1000V.[202] The higher charging rates will allow customers to refill BEVs much more quickly, allowing for extended range trips with refill times that are more similar to conventional ICE vehicles.

If the initial rollout of wireless charging on vehicles proves successful, the market will likely see a proliferation of the technology across many models. If the SAE TIR J2954 standard is any indication, power levels of the systems on future vehicles will increase. OEMs that disclosed product plans which included wireless charging showed that they expect to increase wireless

[202] CAE 2016.

power capability on the vehicles as the technology becomes available. Additionally, OEMs are installing increasing levels of autonomous vehicle capability on more and more models. That technology coupled with wireless charging has the potential to allow vehicles to manage their own charging without human intervention.

### II.B.16. Connected and Autonomous Vehicles (CAV) and Car Sharing

Passenger vehicle technology and travel activity are undergoing a much wider transformation beyond electric drive powertrains. On the engineering front, technology for smart sensors and cloud networking are allowing vehicles to be connected to one another and infrastructure, as well as provide automated driving functionality. Although these are not inherently linked, most industry leaders are creating connected and autonomous vehicles (CAV), and are rushing to market with the innovations due to competition and the interest to provide enhanced safety and convenience services for consumers. These transformations are emerging in the market today, but will become much more widespread in the period after 2025.

In addition to CAV technology innovations, the use profile of passenger vehicles is being transformed as well. As the sharing economy emerged in recent years, vehicle business models began with car sharing (e.g. ZipCar or Car2Go), but now also include ride sharing (e.g. Lyft or Uber). Both of these emerging business models have the potential to dramatically change vehicle ownership models, and use of cars. Some industry leaders and independent experts are beginning to find a nexus between all three of these transformations, and are looking for a way to leverage each other – autonomous, shared, and electric (ASE) – although they do not have to be combined. General Motors' partnership with Lyft to create a CAV on the Bolt EV platform is just one example.[203]

Staff have been studying these trends and are starting to identify research and policy actions that could influence the vehicles' environmental impact. These policy actions bridge across a number of programs at ARB, including vehicle regulations, regional planning, infrastructure development, research, and more. ARB is identifying which actions should be implemented soon to influence business models, compared to research and analysis that should be conducted over a number of years to understand the scale of the environmental and energy impacts. The development of these actions is being coordinated with the California DMV, which has authority over CAV safety rules, Caltrans, the Governor's Office of Planning and Research (OPR), CPUC, U.S. EPA, U.S. DOT, and other agencies.

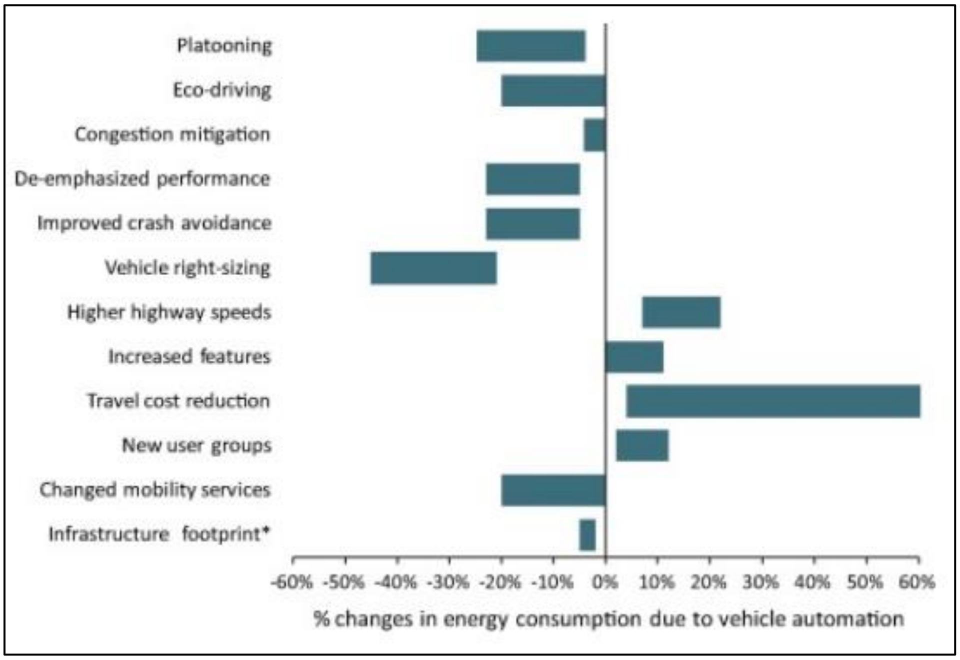
Changes to the vehicle emission regulations to potentially incentivize shared platforms and/or CAVs will need time to evaluate. Recent research has been showing that shared vehicle programs can reduce individual car ownership and encourage advanced vehicle purchases,[204] but has cautioned that the impact on total vehicle miles traveled (VMT), and therefore energy

[203] Gardner, 2016. Greg Gardner. USA Today. "Lyft will be first to get breakthrough Chevrolet Bolt EV." September 28, 2016. http://www.usatoday.com/story/money/cars/2016/09/28/lyft-first-get-breakthrough-chevrolet-bolt-ev/91238266/

[204] TSRC 2016. University of California Berkeley. Transportation Sustainability Research Center. http://tsrc.berkeley.edu/projectarea/innovativemobility

usage, could vary widely from large reductions to large increases.[205] Figure 20 below highlights this potential range of energy consumption from varying elements in this transformation.

**Figure 20 - Estimated ranges of operational energy impacts of vehicle automation through different mechanisms[206]**




Given the uncertainty in CAV impacts on the environment, vehicle regulation changes should not be made in the near term, but rigorous research, analysis, and pilots should be launched to quickly gain further understanding. As an example, connected vehicle functionality has the potential to increase vehicle efficiency, as demonstrated by federal funded research at UC Riverside,[207] but achieving real emission reductions depend on how many vehicles are connected on roadways, whether smart city infrastructure is in place, and whether the vehicles are in urban vs. rural areas. Specifically, connected vehicles could sail through smart intersections with communications to smart streetlights, improving traffic flow. In addition to operational uncertainty, many autonomous vehicle functions are being introduced into the market regardless of vehicle regulations, responding to competition to provide enhanced safety functions for drivers. ARB regulatory teams intend to study these CAV opportunities carefully, but will need further data and evidence of their widespread environmental benefits before adopting rule changes.

Other ARB policy actions should progress more quickly. Research contracts should be established to study ASE innovations in varying forms. ARB's partnerships with the state's air

[205] Wadud 2016. Zia Wadud, et. al. Science Direct. "Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles." February 26, 2016. Transportation Research Part A 86 (2016) 1-18. http://www.sciencedirect.com/science/article/pii/S0965856415002694
[206] Wadud 2016.
[207] CERT 2016. UC Riverside Center for Environmental Research & Technology. "Current Research" http://www.cert.ucr.edu/research/tsr/cr.html

districts and MPOs should be enhanced to help coordinate regional pilot studies, smart city infrastructure, and VMT impact data collection. Opportunities to place electric vehicles in these services and programs should be aggressively supported, which will include strategic consideration of electric charging infrastructure and consumer awareness. The emergence of connected and autonomous, as well as shared platforms is already occurring, but how rapidly they expand into electric drive platforms, and how rapidly the vehicle functions are used in practice, depends on government actions (federal, state, regional, and local). ARB intends to take a leading role to guide this activity.

## *II. C. PEV Costs*

As the PEV market has taken hold in the past five years, and sales have steadily grown, manufacturing has expanded for EVs and major components, bringing production scale and learnings, both resulting in cost reductions. Manufacturing investments are growing rapidly as suppliers and automakers prepare for EV markets around the world.

Many battery manufactures have brought innovation to the market, and a few have been successful enough to expand in production and contract scale to drive costs down. LG Chem and Panasonic are both making large investments as customer contracts are growing. The most unique production investment is Panasonic's partnership with Tesla in the Gigafactory, being completed in Reno, Nevada. The facility, once completed, will produce more batteries than all other global lithium-ion production in 2013.[208] Automakers are also beginning to make large investments in battery manufacturing as technology has evolved. Daimler and Volkswagen have both announced plans to produce packs in partnership with cell suppliers, similar to what Tesla is doing with Panasonic. Nissan was one of the first to do this with their AESC partnership, creating manufacturing hubs in Japan, the UK, and Tennessee.

### II.C.1. Battery Costs

In addition to large advancements in lithium ion battery performance over the past few years, cell and pack costs have also seen dramatic improvements. In the 2012 ACC rulemaking, ARB leveraged battery cost projections from the 2010 TAR which relied heavily on an earlier version of Argonne National Laboratory's BatPaC model.[209] Updated cost projections from Argonne's BatPaC model, in addition to recent public statements from battery and vehicle manufacturers, show costs are declining at a faster rate that assumed in the 2012 rulemaking. Table 7 below is an excerpted table from the ACC ZEV ISOR that showed the battery pack cost assumptions for select years.  For reference, the range designation for the BEV100 and PHEV20 represents all electric range on the UDDS cycle.

[208] Tesla 2016, "Gigafactory", https://www.tesla.com/blog/gigafactory
[209] ANL 2016b. Argonne National Laboratory. "BatPaC: Lithium-Ion Battery Performance and Cost Model for Electric-Drive Vehicles"  http://www.cse.anl.gov/batpac/index.html

**Table 7 - Incremental battery pack (and system) costs used in 2012 ACC rulemaking (2009)**[210]

**Table 5.1: Incremental Direct System Manufacturing Costs* (2009$)**

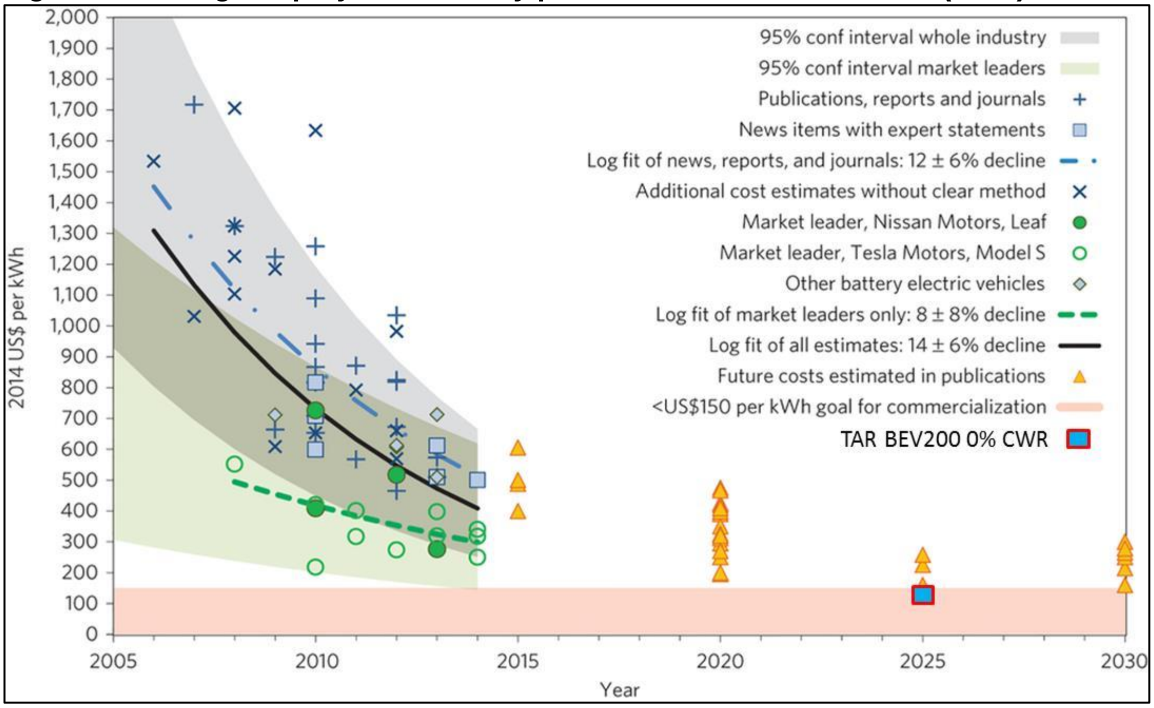
| | 2012 | 2015 | 2020 | 2025 |
|---|---|---|---|---|
| **System per-vehicle costs ($)**[a] | | | | |
| PHEV20 battery pack | 8,078 | 6,462 | 3,309 | 2,647 |
| BEV100 battery pack | 21,367 | 17,094 | 8,752 | 7,002 |
| FCV fuel cell system | 18,908 | 10,208 | 5,220 | 4,756 |
| **System per-unit costs** | | | | |
| PHEV20 battery pack ($/kWh) | 1053 | 842 | 431 | 345 |
| BEV100 battery pack ($/kWh) | 605 | 484 | 248 | 198 |
| FCV fuel cell system ($/kW) | 163 | 88 | 45 | 41 |

*Based on midsize car / small multipurpose vehicle class, as compared to a 2008 baseline; Figures 3 and 4, in Section 2.2.3, show the system costs graphically.

A compilation of varying recent battery pack cost projections is shown in Figure 21 published in a prominent 2015 Nature study.[211] The graphic shows the wide variation in current costs, highlighting how market leaders have a significant cost advantage today. However, the costs begin to converge in 2025 between $200-300/kWh. Many automakers are settling on a few battery manufacturers whose costs have declined recently, although multi-year contracts for initial electric vehicles have locked a few automakers into higher costs until the contracts expire. ARB has added the recent 2016 TAR cost assumption for the BEV200 onto the graph for comparison ($140/kWh at the pack level for a standard size car). As ARB met with manufacturers for the mid-term review, most confirmed aggressive cost projections in the range of $150-200/kWh were reasonable.

[210] ARB, 2011a.
[211] Nykvist, 2015. Bjorn Nykvist, Mans Nilsson. Nature Climate Change. “Rapidly falling costs of battery packs for electric vehicles” March 23, 2015. http://www.nature.com/nclimate/journal/v5/n4/full/nclimate2564.html

**Figure 21 - Range of projected battery pack cost reductions, $/kWh (2014)[212]**




Sue Babinec, a senior commercialization advisor for the U.S. DOE ARPA-E gave a presentation on energy storage technology at the 2016 Advanced Clean Cars Symposium: The Road Ahead. The presentation discussed costs and looked more closely at the 2015 Nature study. While the time based approach of the Nature study is helpful in looking at where the industry is at, an alternative to projecting prices comes by looking at manufacturing volume based effects at a single plant. By aggregating current battery manufacturers and their volumes, one can better extrapolate higher volume prices. The presentation showed that a 35GWh plant could achieve a price of $190/kWh and a 7GWh plant could achieve a price of $235/kWh. The work done by ARPA-E comes at the price and cost issue from a slightly different perspective, and affirms that high volume battery manufacturing will be instrumental in getting costs and prices down.[213]

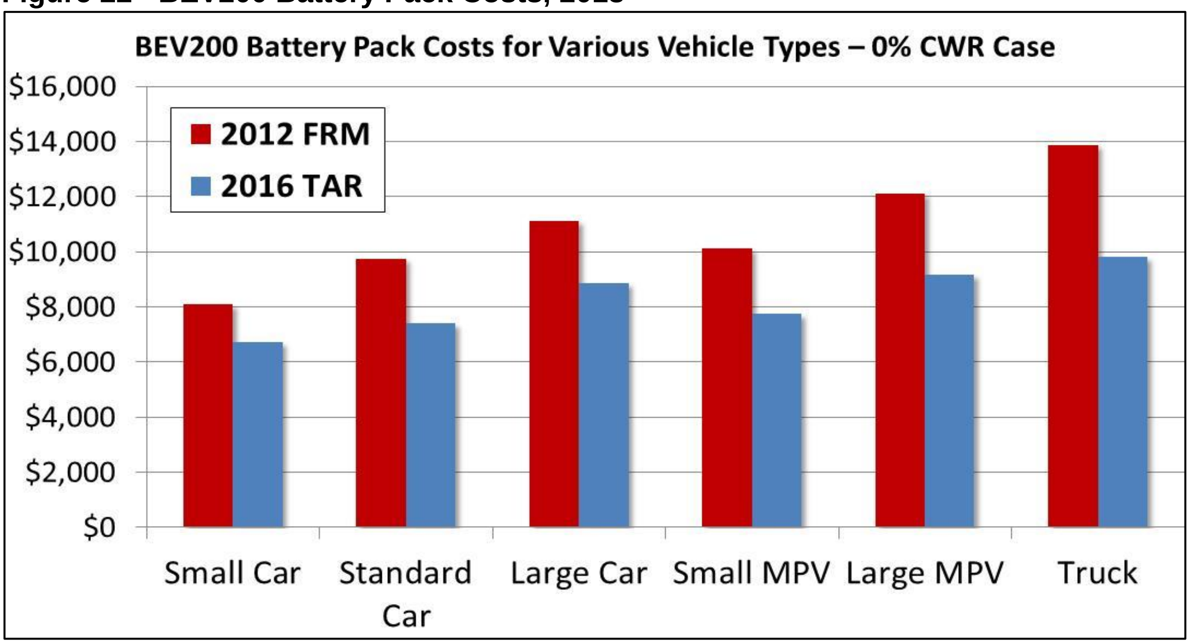
At the 2016 AABC, Dr. Menahem Anderman gave a plenary keynote presentation discussing where Total Battery Consulting, Inc. (TBC) sees the electrified vehicle market going. The team analyzed a 37Ah PHEV NMC (523) metal can cell price at 10 million cells per year. The analysis showed a price of $195/kWh for calendar year 2018 which also included an 8.0% warranty and profit markup. TBC also analyzed a cell similar to what will be used in the Chevrolet Bolt EV. A NMC622 56Ah pouch cell in calendar year 2018 at a production volume at 24 million cells per year came out to $145/kWh. That price included an 8.0% warranty and profit markup and what TBC referred to as “aggressive assumptions”. Dr. Anderman also stated that negotiated contract pricing is dropping faster than costs, and that improvement in manufacturing yields and volume

[212] Nykvist, 2015.
[213] Babinec, 2016.

expansion support lower costs. TBC's analysis, while only showing cell costs, supports the lower costs projected by the 2016 TAR.[214]

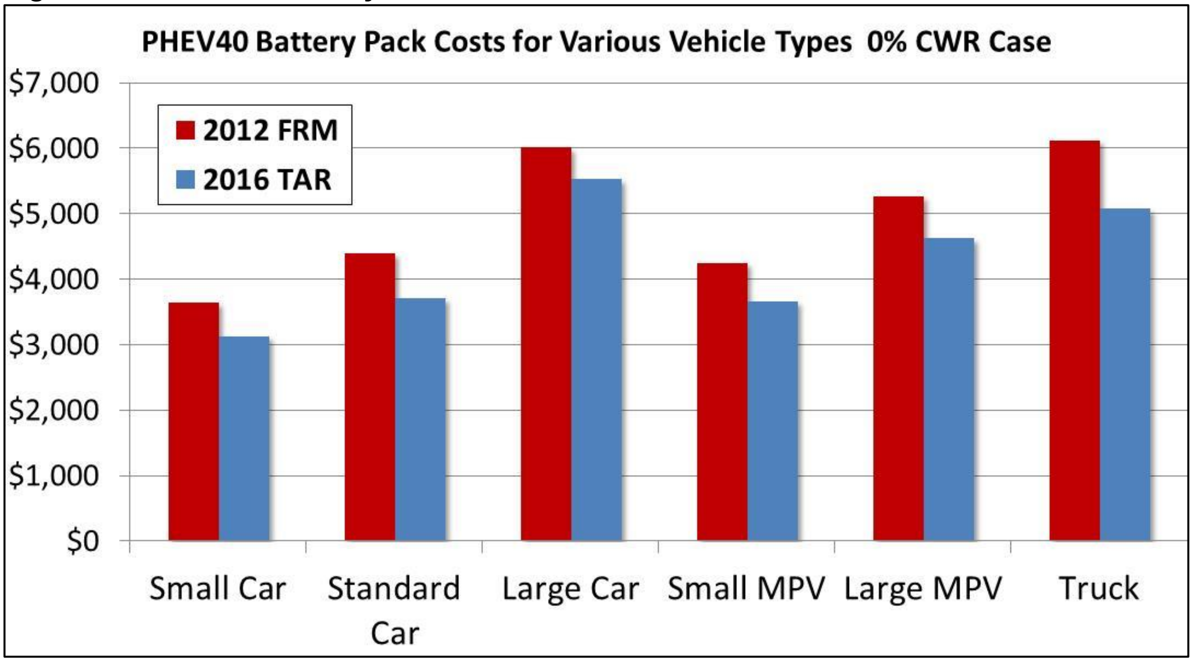
In the 2016 TAR for direct manufacturing costs, U.S. EPA leveraged the ANL BatPaC model to create supply curves for their vehicle cost analysis. The changes in battery cost projections since the 2012 FRM for U.S. EPA's modeling stems from using ANL's most recent BatPaC Version 3 and changes to vehicle component sizing (e.g. usable battery capacity, motor power, energy efficiency, etc) that have resulted in reductions to gross battery capacity and power requirements.[215] Citing a specific excerpt from the 2016 TAR, *"Since the FRM, EV battery pack cost projections have fallen by an average of 24-27% (13-19% per kWh), as a result of better pack topology and cell sizing, reductions in pack capacity and power to energy (P/E) ratio, and other factors. PHEV battery pack costs were lower by 9-12% (2-3% per kWh), for similar reasons."* Figure 22 and Figure 23 below show the full battery pack costs for varying vehicle size classifications from the analysis in the 2016 TAR. The pack costs account for a varying size battery depending on the vehicle load requirements. For the same driving range, a larger pack is required to support the energy demands of larger vehicles.

**Figure 22 - BEV200 Battery Pack Costs, 2013[216]**




[214] Anderman, 2016.
[215] EPA, 2016a. pages 5-346 to 5-347
[216] EPA, 2016a.

**Figure 23 - PHEV40 Battery Pack Costs, 2013**[217]




ARB will continue to study battery technology into the foreseeable future as the technology develops. ARB will also continue to collaborate with the U.S. DOE on its understanding of battery technology and the state of the industry. As new battery cost and performance targets become available from the U.S. DOE and other entities, ARB will utilize those targets in total cost of ownership and vehicle costing models to identify where cost parity of PEVs with conventional ICE technologies may develop.

### II.C.2. Non-Battery Costs

Information on non-battery costs learned from meetings with manufacturers indicates that some of those manufacturers may achieve all of the DOE EV Everywhere non-component battery costs targets before 2022. However, that response was not consistent across all manufacturers and current and projected future costs were not disclosed to staff during those meetings. The 2016 TAR developed the projected non-battery costs by relying heavily on the original FEV contracted tear down of a 2010 Ford Fusion Hybrid that was used in the 2012 FRM. The 2016 TAR's discussion of costs derived using tear-down studies can be found in section 5.3.2.1.1 of the document.

The proliferation of PEV technology since the FEV Ford Fusion Hybrid tear-down study was completed highlights an opportunity to update the non-battery component costs. ARB has contracted with Ricardo to conduct tear down studies of several newer components to update these cost assumptions. Staff will use the results of those tear downs to update non-battery costs when they become available.

[217] EPA, 2016a.

### II.C.3. Rolled Up PEV Costs

Table 8 below compares the previous (2011 ARB ACC ISOR) cost estimates to the updated 2016 TAR (joint agency). While battery costs have been updated to reflect the recent reductions, a nuance in comparing these analyses is that staff now expects to see longer range BEVs relative to what was originally assumed. This means that, compared to the 2012 ARB rulemaking, the newer incremental vehicle costs include a much larger battery pack (BEV200 today vs. a BEV100 from 2011). As a result of decreased battery costs but increased battery packs, the updated incremental vehicle costs for expected vehicles (BEV200) are about the same as they originally were estimated for the lower capability vehicles (BEV100). The incremental price varies from approximately $12,000 to $17,000 for a BEV200.

However, the two platforms most directly comparable show the scale of the battery cost reductions. The BEV75 from the 2016 TAR can be compared to the BEV100 in the 2011 ACC ISOR because ARB's original BEV100 was based on test cycle range and equates to approximately a BEV70 for EPA label range as is used in U.S. EPA's analysis. Comparing these two platforms shows vehicle incremental costs for a shorter-range BEV have declined between 22-36% depending on vehicle size in the 2025 model year.

**Table 8 - Incremental Vehicle Costs (2025 ZEV compared to 2016 ICE vehicle, 2013)**

| 2013 $ | 2011 ISOR (ACC Rulemaking) | | | 2016 TAR (EPA, NHTSA, ARB) ** | | | |
|---|---|---|---|---|---|---|---|
| | BEV100 | PHEV40 | FCEV | BEV75*** | % Diff | BEV200 | PHEV40 |
| Subcompact | $ 11,804 | $ 11,182 | $ 8,189 | $ 7,505 | 36.4% | $ 12,001 | $ 9,260 |
| MdC / SmMPV | $ 12,591 | $ 12,037 | $ 10,174 | $ 8,183 | 35.0% | $ 13,422 | $ 10,554 |
| Large Car | $ 14,566 | $ 15,685 | $ 14,613 | $ 11,355 | 22.0% | $ 16,746 | $ 13,991 |

* ISOR Table 5.4 adjusted to 2013$ with 1.09 CPI factor[218]

** EPA OMEGA EV based on "label" range, ARB is UDDS. "Diff" = EPA BEV75 to ARB BEV100
Label vs. Test adjustment: 0.70

*** 15% weight reduction package

## III. FCEV Technology Status and Trends

The current status of FCEV technology can be illustrated by a comparison between the recent 2014 status reported in the 2016 draft TAR, the historic 2010 TAR reported values, and the future 2020 and ultimate U.S. DOE targets. These targets are based on cost of ownership parity with hybrid drive technology and achievement of U.S. DOE target costs of hydrogen at the pump.

The relative progress of key FCEV technology groups are summarized in Table 9. Several technologies are midway from 2010 to the ultimate targets including, fuel cell (FC) system efficiency, FC system costs, FC durability, and hydrogen storage costs. As the FCEV

[218] ARB, 2011a.

technologies have improved, commercially available vehicles have been introduced. As both the number of available models and sales expand, it is expected that the technology will continue to improve toward the U.S. DOE targets.

**Table 9 - Technology Status and U.S. DOE Targets for Automotive Fuel Cell and Onboard Hydrogen Storage Systems**[219]

| | 2010 TAR | 2014 Status | 2020 DOE Target | Ultimate DOE Target |
|---|---|---|---|---|
| **System Efficiency** | 53-59% | 60% | 65% | 70% |
| **System Cost** | $61/kW ($51/kW)* | $55/kW ($43/kW)* | $40/kW | $30/kW |
| **Fuel Cell System Durability** | 2,500 hrs. | 3,900 hrs. | 5,000 hrs. | 5,000 hrs. |
| **Vehicle Range** | 254 miles | 312 miles ** | | |
| **H2 Storage Costs** | $20/kWh | $17/kWh ($13/kWh)*** | $10/kWh | $8/kWh |

* 2010 TAR values include the then-current 2009 reported status and the 2010 update in parentheses. The 2014 Status includes the reported current cost status and a potential reduced cost based on available or near-term technologies in parentheses.
** Based on U.S. EPA rating for the 2015 Toyota Mirai. The U.S. EPA rating for the 2017 Honda Clarity was recently certified at 366 miles.
*** 2015 AMR reports a current cost status of $17/kWh, but the potential for reduction to $13/kWh in very short term with application of technologies within DOE's funded programs.

## *III. A. Available FCEV Models:*

Currently, three manufacturers (Hyundai, Toyota and Honda) offer FCEV models for sale or lease (see Figure 24).[220,221,222] An additional two models have been announced for future release expanding the breadth of vehicle types to include a four-door sedan, a two-wheel drive SUV, and an all-wheel drive SUV. The available and announced FCEV models are summarized in Table 10 below.

A demonstration all-wheel drive, four-door pickup truck FCEV has been announced by General Motors that will be provided to the U.S. Army for testing in a year's time (see Figure 25). The fuel cell features that the military has indicated are desirable include reliability, instant high torque at any vehicle speed, silent stationary operation, reduced thermal and acoustic signatures (reduced detection), field electricity generation, and fresh water production.[223]

219 EPA, 2016a.
220 Honda 2016a.
221 Toyota, 2016b. Toyota Motor Sales, U.S.A. "Mirai", https://ssl.toyota.com/mirai/fcv.html
222 Hyundai, 2016. Hyundai. "Tuscon Fuel Cell" https://www.hyundaiusa.com/tucsonfuelcell/index.aspx
223 HC, 2016. Hybrid Cars, "Chevrolet ZH2 Colorado Fuel Cell Army Truck is "Mission Ready", 3 October 2016 http://www.hybridcars.com/chevrolet-zh2-colorado-fuel-cell-army-truck-is-mission-ready/. [Accessed 7 October 2016]

**Figure 24 - FCEV Models Available in California now –Toyota, Hyundai, Honda**

**Figure 25 - General Motors Demonstration Military All-wheel Drive Four-door Pickup Truck**[224]

[224] ibid

**Table 10 - Past, Current and Future FCEV Models Available in California**

| Model Year | Manufacturer | Model | Label Range (mi) | Tank (MPa/kg) | Motor (kW) |
|---|---|---|---|---|---|
| 2008-2015 | Honda | FCX Clarity | 231-280 | 35/3.5-4 | 90-100 |
| 2010-2014 | Mercedes | F-Cell | 190 | 70/3.5-3.8 | 100 peak |
| 2014-2017 | Hyundai | Tucson | 265 | 70/5.63 | 100 |
| 2015-Present | Toyota | Mirai | 312 | 70/ 4.8-5 | 114 max |
| 2017-Present | Honda | Clarity | 366 | 70/ 4.5-5 | 130 |
| 2018 | Hyundai | New Dedicated | n/a | n/a | n/a |
| 2018 | Mercedes | GLC F-Cell | 300 | 70/4 | n/a |

Most large vehicle manufacturers have ongoing fuel cell research and pre-production development programs. Manufacturers that are not yet committing to formal production programs point to the lack of fueling infrastructure as the primary reason for a delay in product development. Manufacturers currently offering FCEVs have indicated that they are prioritizing vehicles for areas with multiple hydrogen fueling stations. In the meantime, manufacturers are making agreements with other auto manufacturers or technology providers on fuel cell related research and development. The main goal is to spread risk and costs of complex technology development. Automotive partnerships include GM and Honda, Toyota and BMW, and Daimler, Ford and Nissan.

Toyota partnered with BMW in 2013 to supply BMW with a drivetrain and hydrogen storage technology, which includes the fuel cell stack and system, the hydrogen tank, motor, and battery. The goal is for BMW to produce a commercial vehicle by 2020 and for Toyota to raise production volumes to achieve lower costs.[225] A few days later, Daimler, Nissan, and Ford announced a partnership to jointly invest in FC technology development with an explicit goal of quickly reducing costs by sharing investment capital and leveraging economies of scale.[226] Partnerships of this type can help bring vehicle costs down when new technology is being developed. Later in the same year, General Motors and Honda announced a partnership agreement aimed at developing a joint drivetrain technology that is both more capable and more affordable. As both are leaders in the technology development, their combined product is

[225] GCC, 2013b. Green Car Congress, “BMW and Toyota expand collaboration with work on fuel cell system, sports vehicle, light0weight technology, and Li-air battery” January 24, 2013 http://www.greencarcongress.com/2013/01/bmwtmc-20130124.html (accessed 1/24/13)

[226] GCC, 2013c. GreenCarCongress.com, “Daimler, Renault-Nissan Alliance Ford to develop common fuel cell system; targeting vehicles in 2017” January 28, 2013 http://www.greencarcongress.com/2013/01/fcevs-20130128.html

expected to perform better, leverage consolidation of component supply chains for costs, and bring products to market faster.[227]

## *III. B. FCEV's Anticipated Role in Transport Sector:*

FCEVs are targeted to fit into both the LDV and heavy-duty vehicle (HDV) sectors, both for long-range applications. In particular, the long range and fast refueling times (under five minutes) make FCEVs well suited to demanding duty cycles for larger LDV platforms and HDV applications.

## *III. C. FCEV Basic Technology Components:*

FCEVs are full electric drive vehicles where the propulsion energy typically supplied by a battery is supplied by hydrogen and a fuel cell stack that transforms the stored hydrogen into electricity as needed. The inputs of the electrochemical process for the fuel cell stack are oxygen and hydrogen, with the byproducts being electricity, water, and heat. The major components of the fuel cell system include the fuel cell stack, the hydrogen storage (tank), balance of plant (valves, safety release, vent, fill tubes, etc.), and a battery pack for dynamic load balancing/response, moving the motor directly, capturing braking regeneration, and energy storage. Additionally, the system includes coolant subsystems, an air handling subsystem with compressor-expander module (CEM) precooling, and humidification. A schematic of a typical automotive fuel cell system is shown in Figure 26.

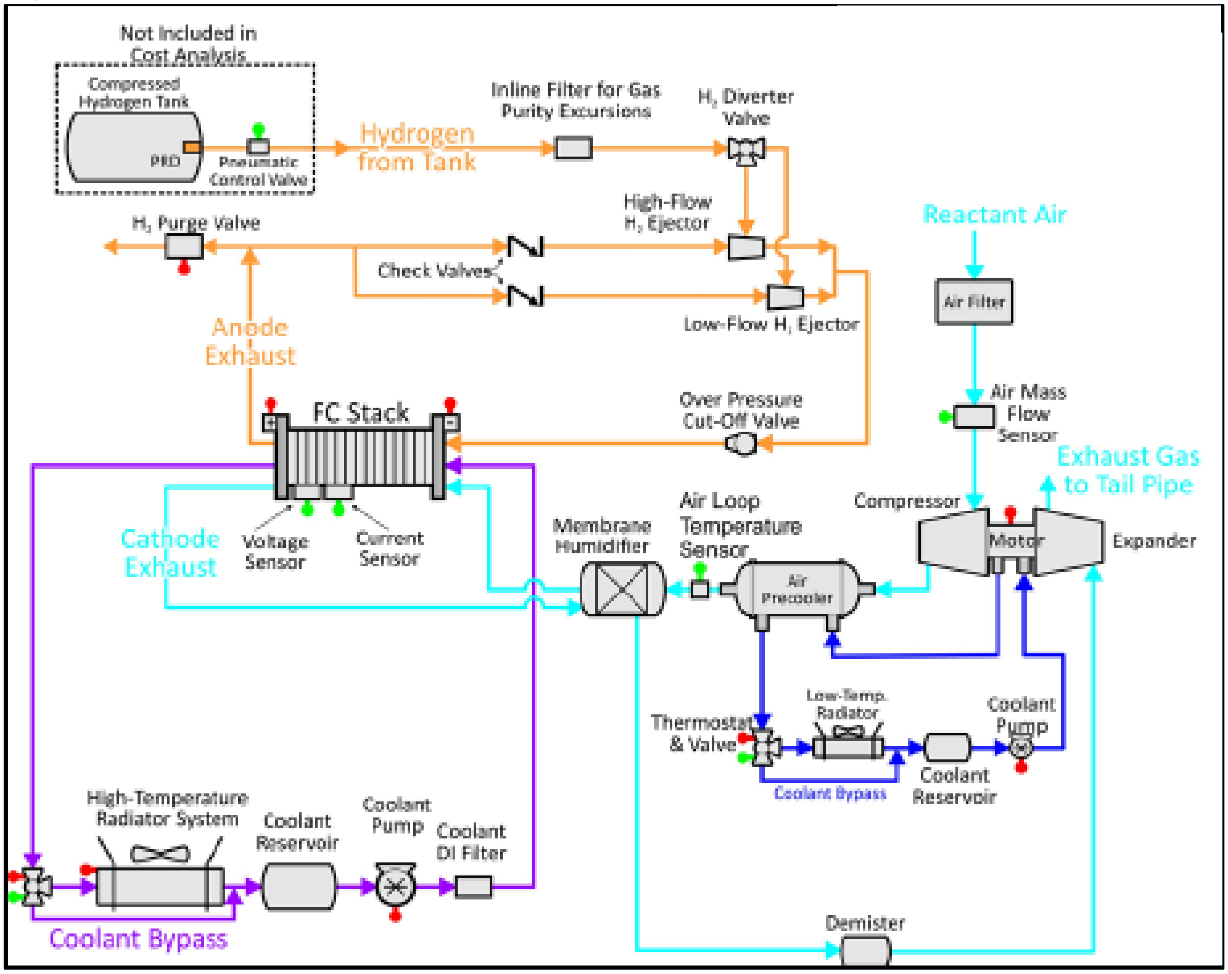
The fuel cell stack is much like a battery in that it consists of an anode, a cathode, and dividing electrolyte membrane (thus the name of the type used for light-duty applications: proton exchange membrane fuel cell).[228] Additional stack components include the gas diffusion layer (GDL) that helps transport hydrogen and oxygen from flow channels to the anode and cathode surfaces, as well as separator plates that divide each individual cell.

An on-board hydrogen storage system for LDVs consists of a 700 bar (70MPa or 10,000psi) hydrogen pressure vessel and the balance of plant (BOP). The tank is typically wound carbon fiber construction with a polymer liner. The BOP consists of devices such as the fill tube and port, temperature sensor, pressure gauge, pressure relief device, rupture disc, solenoid control valve, primary pressure regulator, manual ball valve, a check valve, and related data communications hardware.

[227] Colias, 2013. Mike Colias, Auto News, "GM Honda latest to join forces on fuel cells" July 2, 2013 http://www.autonews.com/article/20130702/OEM05/130709982/gm-honda-latest-to-join-forces-on-fuel-cells

[228] EPA, 2016a.

**Figure 26 - Schematic of Components Included in a Fuel Cell System**[229]




## *III. D. FCEV Technology Trends:*

There have been numerous developments in fuel cell technology in recent years. The broad topics of recent technology trends includes fuel cell stack size reductions through simplification, fuel cell durability, fuel cell platinum use reductions, hydrogen storage production developments, and the advent of the plug-in FCEV (FCPEV).

*Fuel Cell Size:* Recently, there have been significant gains in fuel cell volume reductions. An analysis of the Toyota Mirai design revealed some of the system simplifications that lead to these size reductions: innovative fuel cell stack designs that reduce balance of plant components, simplified humidity management via improved gas diffusion layer (GDL) designs to enhance water flow field design, and lower pressure design to reduce air compressor sizing.[230] Contributing to the reduced size, higher fuel cell system power densities have been achieved

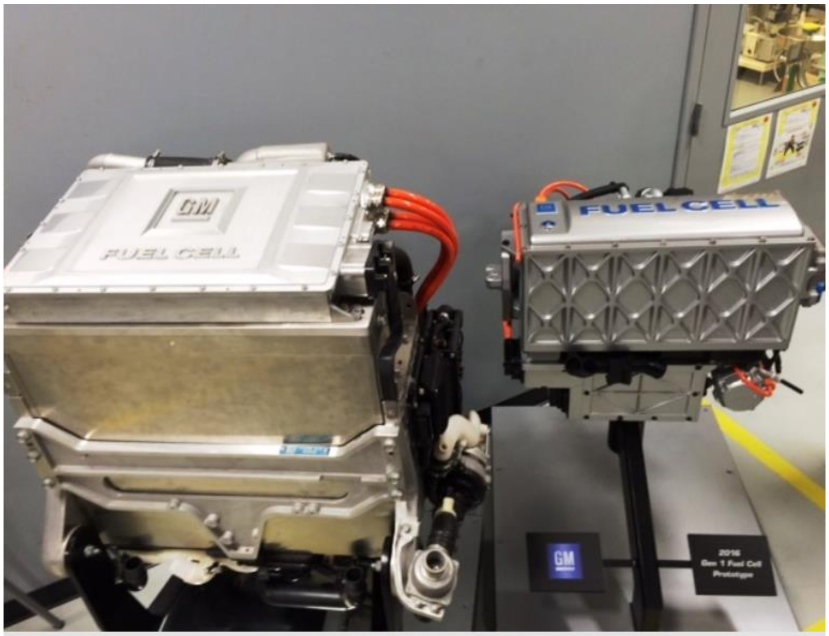
[229] James, 2015. Brian D. James, et al. “Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2015 Update. Strategic Analysis”, December 2015 http://energy.gov/sites/prod/files/2014/11/f19/fcto_sa_2013_pemfc_transportation_cost_analysis.pdf

[230] James, 2016. Brian D. James. “Strategic Analysis Incorporated 2016 Fuel Cell Vehicle and Bus Cost Analysis presentation” at June 9th 2016 DOE Hydrogen and Fuel Cells Program Review Project ID# FC018 https://www.hydrogen.energy.gov/pdfs/review16/fc018_james_2016_o.pdf

via a thinner GDL, a thinner electrolyte, and a more reactive catalyst.[231] Other simplifications to the broader system include consolidation of valve functions (stack inlet shut valve, flow diverter shut valve, stack outlet shut valve, and pressure adjustment valve), removal of the hydrogen diluter, and reducing the number of hydrogen storage tanks from four to two in the vehicles commercially available today.[232]

The magnitude of the fuel cell system advances gained over the past decade can be seen in Figure 27 with the General Motors system. Many manufacturers have stated they can now fit the entire fuel cell system in the conventional vehicle engine compartment enabling the use of standard vehicle platforms and maintaining expected passenger space for FCEVs.

**Figure 27 - General Motors FCEV System Size Improvements Depicted Over a Ten-Year Period*[233]***




**First-generation GM FCEV system (left), 2016 prototype (right).**

*Fuel Cell Durability*: Durability of the fuel cell stack has improved over 50% in four years (see Table 9). In an effort to continue the durability improvement trend, Toyota has developed technology to observe and better understand the degradation process of the platinum catalyst in

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[231] Tejima, 2016. Tejima G. "2016 Technology Developments to Enable FCEV Manufacturing at Scale", Toyota Motor Company presentation at the 2016 CARB Advanced Clean Cars Symposium: The Road Ahead September 27th. https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/technology_developments_to_enable_fecv_manufacturing_at_cale_go_tejima.pdf

[232] GCC, 2016f. Green Car Congress, "2016 Toyota Details Design of Fuel Cell System in Mirai; Work on electrode catalysts". April 19, 2016. http://www.greencarcongress.com/2016/04/20160419-toyota.html

[233] Amend, 2016. James Amend. Ward's Auto. "GM Says FCEVs Developing too quickly for production". February 17, 2016. http://wardsauto.com/engines/gm-says-fcevs-developing-too-quickly-production

the fuel cell at a scale not able to be studied before. Toyota explains, "…the mechanism behind the degradation phenomenon of platinum nanoparticles has not been fully understood. This is largely due to the technical difficulty in directly observing the nanometer-sized platinum particles in liquid electrolyte under applied electrochemical potentials."[234] Three platinum degradation mechanisms were described: 'aggregation' where multiple platinum particles migrate together and form into one large particle (lowers surface area), 'dissolution and reduction' where platinum ions move from one particle to another resulting in the same end state as in aggregation, and 'fall off' where carbon oxidization with high electrolytic potential causes the platinum particles to fall off. The durability issue directly affects the amount of platinum required to achieve and maintain adequate catalytic activity.

*Platinum Use:* As recently as 2012, platinum comprised 37% of the fuel cell system costs.[235] Recent efforts have reduced the minimum amount of platinum required for fuel cell catalysts by fivefold.[236] This area remains a key priority for U.S. DOE and auto manufacturer research efforts. Nano technology developed in the laboratory shows promise of even more reductions. The use of platinum coated nanoframes provides better surface area per mass of platinum and has achieved a threefold increase in mass activity.[237] Past advancements include better platinum utilization through: improving active surface area, improved gas transport (and thus reactions), and improved proton transport (less loss of efficiency).

*Hydrogen Storage:* Past developments in hydrogen storage technologies have shown gains in performance and cost reductions. For example, in 2014, Toyota was able to leverage 100 years of textile industry experience to wind carbon fiber tanks six times faster than the industry standard at the time and at higher quality.[238] Additionally, aluminum and steel lined tanks that were injection molded were replaced with polymer linings that are blow molded with better wall thickness accuracy, better containment of the hydrogen molecules, and better durability against stress from constant heat changes due to rapid hydrogen filling.[239]

The current state of hydrogen storage technology consists of compressed hydrogen stored in carbon wound tanks at 700 bar (70MPa or 10,000psi). This technology is the best available current option when considering cost, volume, and weight collectively. Unfortunately, strength

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[234] Kato, 2016. Kato, H., SAE Int. J. Alt. Power. "In-Situ Liquid TEM Study on the Degradation Mechanism of Fuel Cell Catalysts," 5(1):189-194, 2016, doi:10.4271/2016-01-1192

[235] Papageorgopoulos, 2012. Papageorgopouls Dimitrios, U.S. Department of Energy. "Fuel Cells" Annual Merit Review and Peer Evaluation Meeting Presentation May 14, 2012. https://www.hydrogen.energy.gov/pdfs/review12/fc_plenary_papageorgopoulos_2012_o.pdf

[236] DOE, 2016f. U.S. Department of Energy Office of Energy Efficiency & Renewable Energy. "Fuel Cell Technologies Office Accomplishments and Progress, September 28, 2016. http://energy.gov/eere/fuelcells/fuel-cell-technologies-office-accomplishments-and-progress

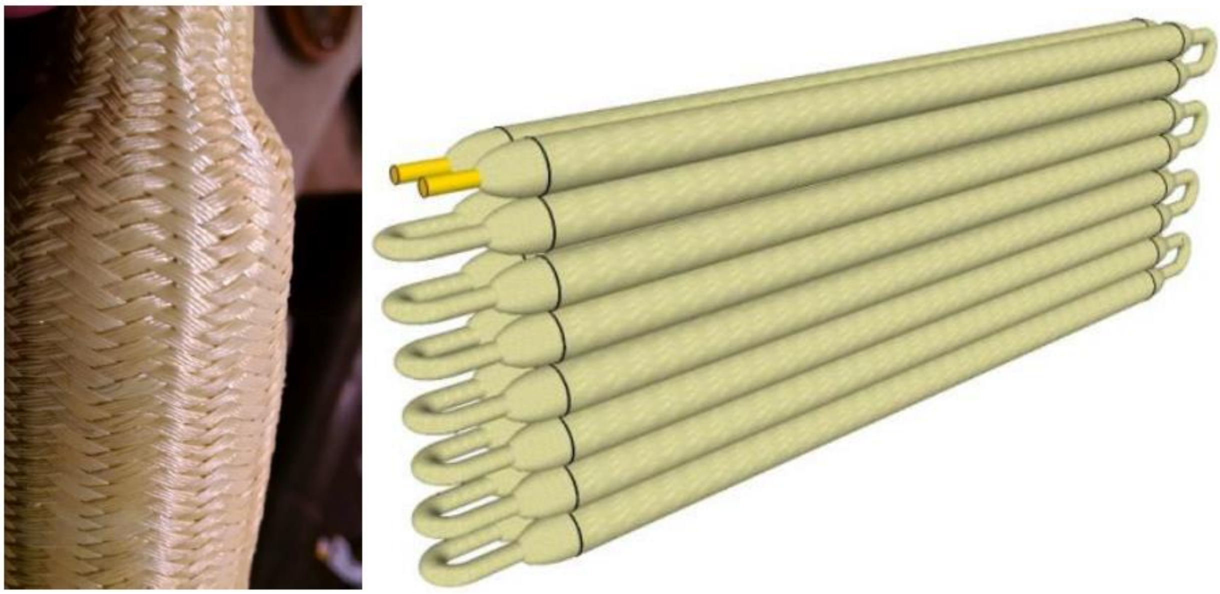
[237] Satyapal, 2015. Satyapal, Dr. Sunita. U.S. Department of Energy. "U.S. Department of Energy Hydrogen and Fuel Cells Program" March 2, 2016. http://energy.gov/sites/prod/files/2016/03/f30/fcto_fc_expo_2016_satyapal.pdf

[238] Blanco, 2014. Sebastian Blanco. Auto Blog. "How Toyota's 100-year textile history influenced FCV hydrogen fuel cell car", September 10, 2014. http://www.autoblog.com/2014/09/10/toyota-100-year-textile-history-fcv-hydrogen-fuel-cell-car/

[239] PT, 2016. Plastics Today. "Polyamide makes its mark in high-pressure hydrogen tank for Toyota fuel cell vehicle", May 31, 2016. http://www.plasticstoday.com/polyamide-makes-it-mark-high-pressure-hydrogen-tank-toyota-fuel-cell-vehicle/168249825924709

requirements can only be satisfied by a cylindrical shape, which possess difficulties for manufacturers to fit them into the vehicle. However, future packaging advancements may reduce the space needed for storage in the vehicle. For example, the concept of “conformable tubes” is being explored where thick but strong tubes can be wound back and forth in more convenient shapes than a large cylinder but are still long enough to store sufficient hydrogen and may offer up to a 20% storage density improvement (see Figure 28).[240]

**Figure 28 - Conceptual Image of Conformable Tubes for Compressed Hydrogen Gas On-board Storage**



The future of hydrogen storage has several promising non-gaseous developments that are not yet fully developed for commercial production. A summary of the various technology alternatives and their 2015 status are shown in Figure 29 which represents the alternatives’ current performance projections. The plot indicates that cryo-compressed or liquid hydrogen may have weight and volume advantages to compressed gas. Chemical hydride storage may have equal weight characteristics but a slight advantage on volume.

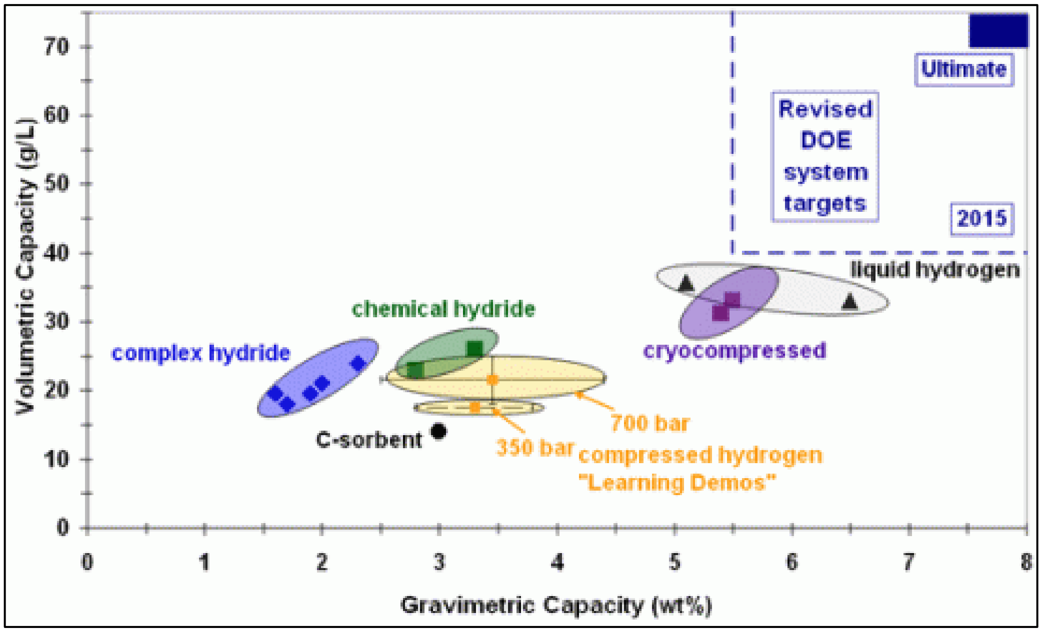
Cryo-compressed hydrogen offers potentially 50% more storage capacity than gaseous storage given a design space typical of a passenger vehicle and accounting for additional tank insulation. There are also infrastructure advantages as it does not require the same high pressure (350bar or less) improving the cost of operating a refueling station and its associated reliability. Additionally, the hydrogen is already cold and therefore no communication with the vehicle is required for monitoring tank refueling temperatures as is currently done during fueling for gaseous high compression systems to ensure safety.  However, the cost of the on-board storage tank, the cost of cooling the hydrogen, and the cost of boil-off in the vehicle remain

[240] Stetson, 2016. Stetson N. “Technology Developments to Enable Hydrogen On-board Storage Manufacturing at Scale”, Presentation at CARB Advanced Clean Cars Symposium: The Road Ahead. U.S. DOE. September 27th. https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/technology_developments_to_enable_hydrogen_onboard_storage_manufacturing_at_scale_ned_stetson.pdf

challenges of this technology.  These are similar benefits and issues for liquid hydrogen systems.[241]

Complex hydride, chemical hydride, and C-sorbent hydrogen storage technologies are not yet developed to performance specifications suitable for consumer goods and are subsequently cost prohibitive.

**Figure 29 - 2015 Status of Hydrogen Storage Technologies (Does not represent eventual potential)*[242]***




*FCPEVs:* Daimler has recently announced the pending release of the Mercedes-Benz GLC F-cell: the world's first production fuel cell plug-in hybrid electric vehicle (FCPEV) (see Figure 30). The vehicle will have a 9kWh battery that will provide up to 30 miles of grid-supplied electric range on battery only, a combined total range of 300 miles, and will be an all-wheel drive SUV. A 4kg hydrogen tank compressed to 700-bar will provide the balance of the vehicle's range.

Daimler claims a 30% reduction in fuel cell system size (from previous versions) that will fit entirely into the engine compartment and a 90% reduction in platinum for the stack therefore

[241]DOE, 2012b.  U.S. Department Of Energy. "Fuel Cell Technologies Office Multiyear Research, Development, and Demonstration Plan, Chap 3." May 2012. http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

[242] DOE, 2016g. Department of Energy. "Status of Hydrogen Storage Technologies, Office of Energy Efficiency & Renewable Energy" September 28, 2016. http://energy.gov/eere/fuelcells/status-hydrogen-storage-technologies

substantially lowering costs. Daimler has indicated it believes this vehicle has the potential to improve the economics of the hydrogen fuel supply in light-duty transportation.[243]

**Figure 30 - Preproduction Image of Model Year 2018 Mercedes GLC FCPEV[244]**


Specifically, Daimler claims the FCPEV has the potential to partly mitigate one of the near term barriers to FCEV implementation, namely, a limited hydrogen fueling infrastructure. Since the GLC can travel 20-30 miles on battery alone, the battery may be able to provide a typical user with enough range to meet approximately one-third of their travel needs.[245] Thus, the frequency with which a driver would need to visit a hydrogen refueling station could be reduced, depending on the size of the on-board hydrogen storage capacity. Based on standard travel and choice model principles, this will increase the distance a driver is willing to drive out of their way to refuel on hydrogen, which may be necessary given a limited hydrogen refueling infrastructure. Additionally, drivers may be less reliant on refueling stations overall as they have the option to plug in with electricity. These two factors combined may offer some mitigation to the interim limited access to infrastructure.

## *III. E. FCEV Cost Trends:*

The cost of an FCEV has come down dramatically in recent years. For example, the 2015 Mirai FCEV costs 1/20th that of the Toyota Highlander FCHV-adv, which was available for lease only in Japan starting in 2008[246] (available for pilot fleets elsewhere). As the motor and power electronic components are not unique to the FCEV (they are similar and may even be shared

[243] Daimler, 2016c. Daimler Global Media. "Under the microscope: Mercedes-Benz GLC F-Cell: The fuel cell gets a plug," September 26, 2016. http://media.daimler.com/marsMediaSite/en/instance/ko/Under-the-microscope-Mercedes-Benz-GLC-F-CELL-The-fuel-cell-.xhtml?oid=11111320

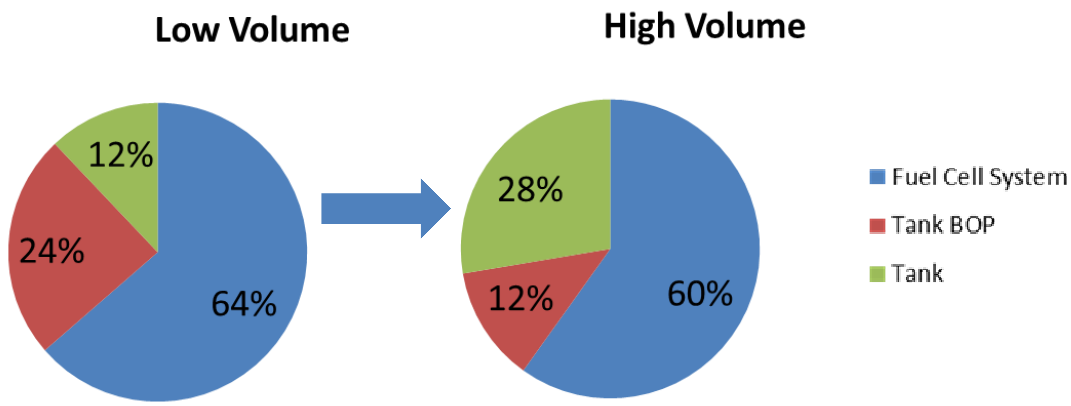
[244] Ayapana, 2016. Erick Ayapana. Motor Trend. " Mercedes GLC F-cell Is World's First Hydrogen Plug-in Vehicle, 2016, Motor Trend, Accessed 9/28/16. http://www.motortrend.com/news/mercedes-glc-f-cell-worlds-first-hydrogen-plug-vehicle/

[245] Based on comparable electric range from Ford C-Max and Fusion Energy eVMT results in Appendix G.

[246] Tejima G. 2016 Technology Developments to Enable FCEV Manufacturing at Scale, Toyota Motor Company presentation at the 2016 CARB Advanced Clean Cars Symposium: The Road Ahead September 27th. https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/technology_developments_to_enable_fecv_manufacturing_at_cale_go_tejima.pdf

with BEV and HEV drivetrain components), their manufacturing scale can be leveraged; but they are not discussed in this section. The cost split between the remaining systems is depicted in Figure 31 for both low volume production levels (current) and high volume production levels (future). As the cost of a FCEV is more than a conventional vehicle, the relative cost magnitude of each component is important to understand.

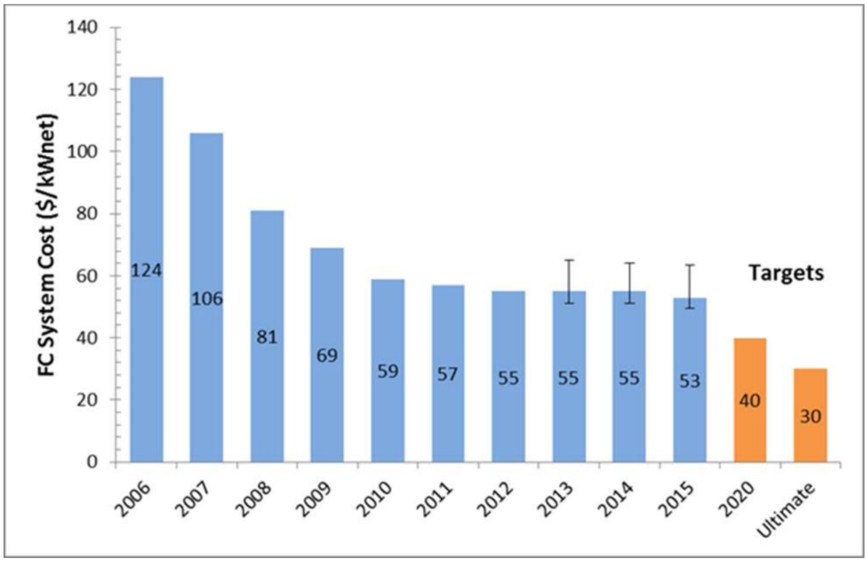
**Figure 31 - Percent Split between Fuel Cell System Components for Low and High Volume Production Levels**[247]




*Fuel Cell System Cost:* These costs are projected for 500,000 units of production per year and have associated federal U.S. DOE targets in '$ / kW' of power output capacity. A history of the high-volume cost projections, published by the U.S. DOE each year since 2006, is shown in Figure 32 along with their targets for 2020 and beyond. These targets are based on cost of ownership parity with hybrid drive technology and achievement of U.S. DOE target costs of hydrogen at the pump. As shown, the high volume cost projections for fuel cell systems has declined substantially.

[247] EPA, 2016a.

**Figure 32 - History of U.S. DOE Fuel Cell Cost Projections for 500,000 Production Units per Year**[248]




To get a better idea of current fuel cell production costs, the U.S. DOE cost projections are shown again in Figure 33 but this time with the additional axis of production volume. With the data shown, the evolution in cost variation according to production volume over the past several years can be assessed. What the costs could be if production was 500,000 units per year is reiterated at the front facing corner of the plot.

Pulling from these projections and fitting a curve, staff can produce estimates on any input value. For example, at 100,000 systems per year, an 80kW system is projected by this analysis to cost approximately $5,500; a 100kW system would cost approximately $6,200 (in 2014).

[248] DOE, 2016h. U.S. Department of Energy. "Fuel Cells Program Area - Plenary Presentation" June 6-10, 2016. https://www.hydrogen.energy.gov/pdfs/review16/fc000_papageorgopoulos_2016_o.pdf

**Figure 33 - Fuel Cell System Cost Projections by Year of Projection and Production Units per Year**

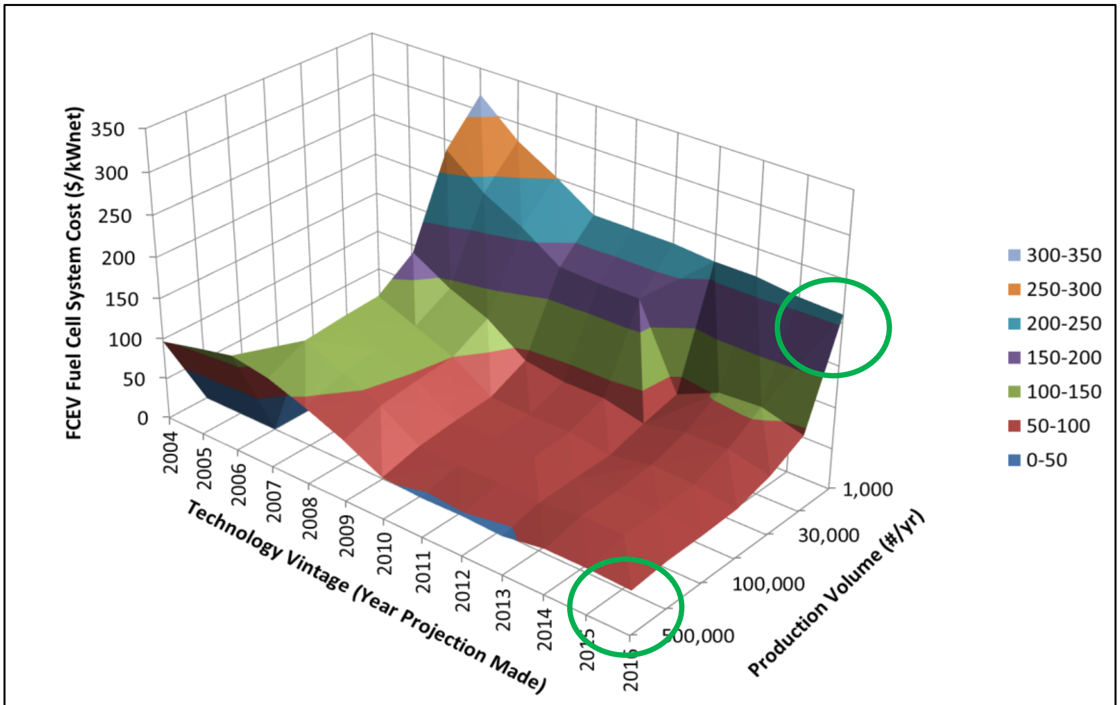



Figure developed by ARB based on data reported in DOE-funded annual reports prepared by TIAX, LLC and Strategic Analysis, Inc. in the years 2004-2016.

*Hydrogen Storage Systems:* A 2014 analysis estimated an on-board hydrogen storage system (tank and BOP) cost of $16.76/kWh (approximately $660/kg of storage capacity). Prior to 2020, using near term developments, these costs could be reduced to $12.99/kWh (approximately $510/kg) (2015 AMR). A summary of the storage costs and performance status versus U.S. DOE targets is shown in Table 11. Current compressed gas storage costs are twice ultimate targets and are not expected to fully reach the ultimate U.S. DOE targets in the near term.

**Table 11 - Summary of Hydrogen Storage Targets for Performance and Cost with Status of Various Technologies**[249]

| Storage Technology | Cost ($/kWh), [$/kg] | Gravimetric Density (kWh/kg), [kgH2/kg system] | Volumetric Density (kWh/L), [kgH2/L] |
|---|---|---|---|
| 2020 DOE Target | 10, [333] | 1.8, [0.055] | 1.3, [0.04] |
| Ultimate DOE Target | 8, [266] | 2.5, [0.075] | 2.3, [0.07] |
| 700 Bar Compressed | 17 | 1.5 | 0.8 |
| 350 Bar Compressed | 13 | 1.8 | 0.6 |
| Metal Hydride | 43 | 0.4 | 0.4 |
| Sorbent | 15-16 | 1.2 | 0.6-0.7 |
| Chemical | 17-22 | 1.1-1.5 | 1.2-1.4 |

[249] EPA, 2016a.

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